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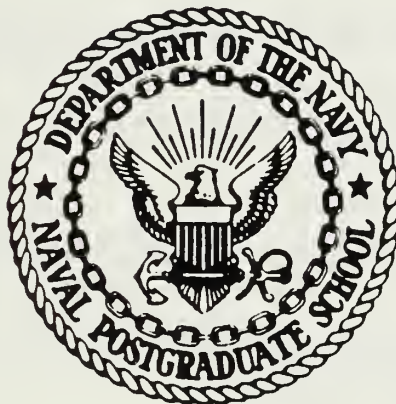






# NAVAL POSTGRADUATE SCHOOL

## Monterey, California



# THESIS

THE EFFECT OF TEMPERATURE ON THE TENSILE  
PROPERTIES OF HSLA-100 STEEL

by

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June 1987

Thesis Advisor:

Kenneth D. Challenger

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<p>High Strength Low Alloy (HSLA) steels have been shown to possess high strength and toughness. Additionally, these steels can be welded without the normal preheating required by comparable HY-series steels. HSLA-100, 100 Ksi yield strength, contains increased amounts of copper, manganese and nickel over the currently certified HSLA-80. However, prior to use in Naval ship construction knowledge of the steels toughness behavior is necessary. Existing fracture mechanics models are not applicable to HSLA-100 steel because HSLA-100 has only 0.04% carbon and these models use carbides as the nucleation site for cleavage fracture. This research is part of a program to investigate and model the micromechanics of deformation and fracture of HSLA-100.</p> <p>Tensile testing of hourglass shaped specimens was conducted at quasi-static strain rates. Individual tensile test temperatures ranged from 24 C to -196 C. True</p>					
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The Effect of Temperature on the Tensile  
Properties of HSLA - 100 Steel

by

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Lieutenant, United States Navy  
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Submitted in partial fulfillment of the  
requirements for the degree of

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## ABSTRACT

High Strength Low Alloy (HSLA) steels have been shown to possess high strength and toughness. Additionally, these steels can be welded without the normal preheating required by comparable HY-series steels. HSLA - 100, 100 Ksi yield strength, contains increased amounts of copper, manganese and nickel over the currently certified HSLA - 80. However, prior to use in Naval ship construction knowledge of the steels toughness behavior is necessary. Existing fracture mechanics models are not applicable to HSLA - 100 because HSLA-100 has only 0.04% carbon and these models use carbides as the nucleation sites for cleavage fracture. This research is part of a program to investigate and model the micromechanics of deformation and fracture of HSLA-100.

Tensile testing of hourglass shaped specimens was conducted at quasi-static strain rates. Individual tensile test temperatures ranged from 24 C to -196 C. True stress, corrected for necking, and true plastic strain were monitored throughout the tests. This allowed a comparison to be made between the plastic strain behavior of HSLA - 100 steel and a traditional constitutive equation used to describe the stress-strain behavior of metals.

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## I. INTRODUCTION

### A. DEVELOPMENT OF COPPER BEARING HSLA STEELS

The problems associated with welding quenched and tempered high alloy and plain carbon steels are well documented [Refs. 1,2]. The high cost of manufacturing and producing satisfactory critical welds in these conventional steels combined with the desire for higher strength weldable materials has led to the development of High Strength Low Alloy (HSLA) steels. These steels utilize small microalloying element additions while keeping carbon below 0.15% to develop the desired strength and toughness levels.

The variety of steels classified as high strength low alloy (HSLA) has expanded greatly over the past decade. Originally the classification applied strictly to carbon - manganese steels which were microalloyed with niobium, vanadium or titanium. The category of HSLA steels now includes acicular ferritic or low carbon bainitic steels, higher carbon more pearlitic steels, quenched and tempered steels, dual phase steels, and cold rolled and tempered steels. This paper will deal with acicular ferritic HSLA steels where copper is the primary strengthening microalloying constituent. When referring to HSLA steels herein this is the intent.

The ability of Cu additions to strengthen steels has been known since the 1930's; however, commercial development and production was slow to proceed until the late 1960's [Ref. 3]. The key reason for the slow progress in developing this type of HSLA steel was the deterioration of the hot working properties of Cu bearing steels [Refs. 4,5]. Once the problem of "hot shortness" was overcome a rapid development of a variety of Cu bearing HSLA steels followed.

During the 1970's several Cu bearing low alloy steels with similar chemical compositions were developed and tested. Various trade names are: NICOP, IN-787, and NICUAGE TYPE 1. High yield strength, above 70 KSI, improved weldability, toughness, ductility, and corrosion resistance over conventional steels has been reported for these new HSLA steels. [Refs. 6,7,8]

The military has certified a low alloy Copper - Nickel steel for structural uses, which is quite similar to the above mentioned commercial steels, designated HSLA - 80. The chemical composition of HSLA - 80 (MIL-S-24645) is listed in Table I of Appendix A which is taken in its entirety from Reference 9.

## B. INFLUENCE OF ALLOYING ELEMENTS ON HSLA STEELS

A portion of the Fe-Cu phase diagram is shown in Figure 1 [Ref. 10]. Wilson [Ref. 5:pp. 164-165] has verified that a sufficiently hardenable Fe-Cu alloy can be made to transform

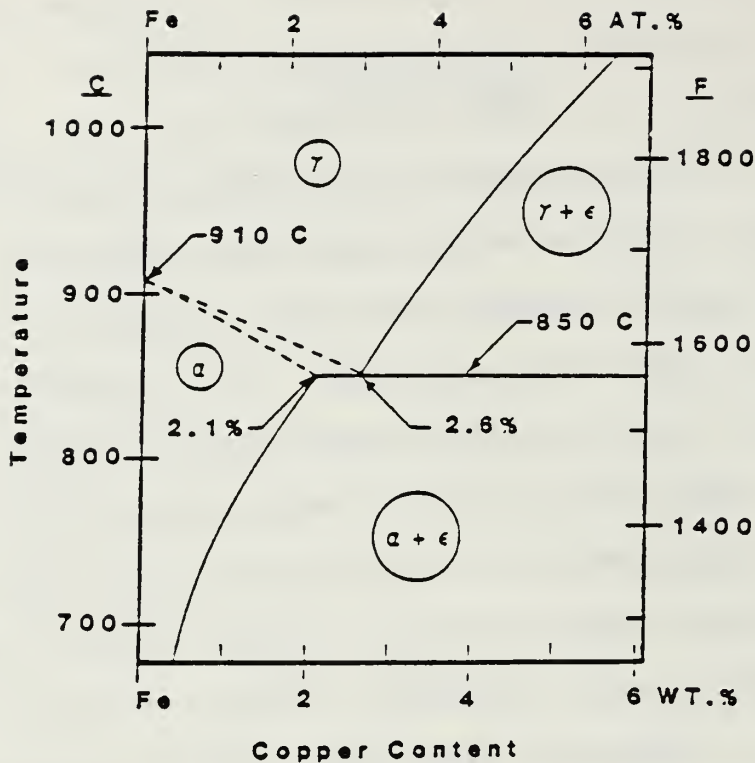


Figure 1. Iron Rich End of the Fe-Cu Phase Diagram

from the austenite region to form martensite and supersaturated ferrite. As the solubility of copper in ferrite is less than in austenite some copper may precipitate in the ferrite however, the equilibrium solubility is not reached on cooling. Subsequent aging heat treatment then produces high strength levels by uniform precipitation of a copper rich epsilon phase which appears as rods or spheres. Quenching from elevated austenitizing temperatures causes significantly more copper to remain in solid solution than air cooling. The subsequent precipitation of epsilon copper particles in the ferrite by

heat treating provides the primary strengthening mechanism of this type of HSLA steel. [Refs. 11,12]

The microstructure of HSLA - 80 (Class 3 - quenched and aged) varies, ( depending on cooling rate from the austenitization temperature ), from polygonal/acicular ferrite at high cooling rates ( thin plates ) to a polygonal ferrite matrix with dispersed groups of cementite particles for slower cooling rates ( thicker plates ) [Ref. 10:pp. 7-12]. Steels with acicular ferrite microstructures exhibit much higher strength than those with polygonal ferrite microstructures [Ref. 13]. Acicular ferrite, synonymous with bainitic ferrite, differs from polygonal ferrite in that acicular ferrite exhibits lath like ferrite grains containing a high dislocation density. A key addition to HSLA - 100 is niobium. Its addition to these copper bearing steels is primarily for grain size refinement. This is accomplished in two ways, by the precipitation of niobium carbonitrides during the austenitization (class 3 plates) process and by retarding austenite recrystallization during hot rolling [Ref.12:pp. 656-659]. Niobium also provides some precipitation hardening effect.

In these steels the potential problem of hot shortness, the formation of low melting point copper rich phases which can cause fissured surfaces during thermal mechanical processing, is prevented by nickel additions to copper bearing steels. However, the primary reason nickel is added

to these steels is its beneficial effect on toughness. As with niobium, a strength increase is also observed with nickel additions. Finally, since nickel remains with copper during remelting, scrap can be used in melts of other steels without the potential harmful effects of copper alone [Ref. 14 ].

Chromium and molybdenum are necessary to retard the epsilon copper precipitate nucleation and growth, during quenching from the austenitizing temperature, known as auto-aging. This enables closer control of the finished product and thus more consistency in mechanical properties. [Ref. 15]

Manganese, as with chromium and molybdenum helps to suppress polygonal ferrite formation, thus adding transformation substructure strengthening to these steels' overall strengthening components [Ref. 10:pp. 3-4]. Manganese increases the hardenability of HSLA steels as it does conventional steels.

Silicon is added as a deoxidizer and the aluminum present acts to enhance grain refinement. Impurity elements such as phosphorous and sulfur are kept to a minimum by direction in the military specification for HSLA - 80. The concern with phosphorous is embrittlement caused by the formation brittle iron and nickel phosphides [Ref. 1: p. 98]. Sulfur is kept as low as possible because a steel's susceptibility to lamellar tearing is proportional to the



sulfur content [Ref. 16]. This is accomplished by a low sulphur practice such as vacuum degassing and argon injection with CaSi or Mg for sulfide shape control, as specified in Appendix B.

#### C. INFLUENCE OF HEAT TREATMENT ON HSLA STEEL PROPERTIES

The ASTM heat treatment applicable to the copper bearing HSLA steels discussed herein is Class 3 ( quenched and precipitation hardened). For HSLA - 80 the austenitizing temperature range is 870 to 970 C (1600 to 1700 F). After water quenching, approximately 450 Mpa ( 65 Ksi ) of the total expected 550 MPa (80 Ksi) yield strength is attained. Precipitation hardening at 540 to 665 C ( 1000 to 1225 F) supplies the remaining portion of the desired yield strength. This precipitation strengthening more than offsets any softening occuring at the precipitation heat treatment temperature. [Ref. 12:p. 656]

##### 1. Temperature effect on precipitation hardening

In order to achieve the desired levle of strength, toughness and weldability of the precipitation hardenable steels, various aging temperatures/times are used. There are three ASTM classifications for precipitation hardenable steels. Class 1 designated as-rolled plus precipitation hardened, yields the highest strength levels. Class 2 is normalized plus precipitation hardened, this produces a lower strength than Class 1 but improved toughness. Class 3

is quenched plus precipitation hardened, this Class provides the best overall level of toughness with strengths comparable to Class 1. As noted earlier a Class 3 precipitation heat treatment is required to provide the fine grained acicular ferrite microstructure. Jesseman and Murphy [Ref. 12:pp. 656] note that at this stage of production "the relatively soft as-rolled, as-normalized or as-quenched conditions have good ductility and moderate toughness. Cold forming at this stage is sometimes advantageous because lower press capacities are required." Then precipitation heat treating can ameliorate the effects of straining and aging on toughness. It is noteworthy that post weld precipitation hardening can serve as a simultaneous stress relief thus reducing overall fabrication costs [Ref. 3:pp. 445-449]. Since diffusion of copper in ferrite is involved in the strength determination of these steels, both the time and the temperature of the precipitation heat treatment is important. Jesseman and Murphy [Ref. 12:pp. 657-658] concluded that treating above 565 C (1050 F) produced a gradual softening. The rate of this softening was slow, due to the additions of molybdenum and chromium, and thus easily controllable. Additionally, raising the precipitation heat treatment temperature to 595 C (1100 F) or above markedly improved CVN impact energy in Class 2 and Class 3 plates.

## 2. Time effect on precipitation hardening

The mechanical properties of copper bearing HSLA steels are largely determined by the size and amount of the epsilon-copper precipitates. These in turn are governed by the aging treatment. The workers in Reference 17 report that overaging is desirable. Overaging promotes high toughness and it reduces the sensitivity of the steel to additional heating below the austenitizing temperature which could occur during welding or bending/shaping operations. Also, overaging was reported to lead to high toughness. Testing reported in Reference 12 revealed that the effect of time at aging temperature was notably less significant than the effect of temperature itself. Similar results were reported in Reference 17, where Class 3 steels only underwent a small change in properties when the aging time was varied thirty minutes at 899 C (1650 F). Several papers in the Conference Proceedings of International Conference on Technology and Applications of HSLA Steels 3-6 October 1983 Philadelphia, Pennsylvania noted that degraded mechanical properties were restorable by reaustentization and aging treatment.

## II. BACKGROUND

### A. STRESS - STRAIN RELATIONSHIPS

Many mathematical formulations have been developed to relate stress and strain in metals. Historically the relations developed attempted to relate stress - strain behavior from the onset of loading to the point of fracture. No single relation has gained universal acceptance due to problems associated with describing elastic and plastic behavior in a single equation. As a result, although many expressions have been developed since Hooke's law was introduced in 1678, many are of limited utility [Ref. 18].

When a material has experienced plastic deformation the linear relationship between stress and strain, described by Hooke's law, is no longer applicable. Figure 2 depicts a general stress - strain diagram for a material without a pronounced yield point [Ref. 19]. The figure depicts the elastic region and two regions of plastic deformation. In the elastic range stress is directly related to strain through a constant of proportionality. Hooke's law can be expressed as:

$$S = E e$$

Where  $S$  is the applied stress and  $e$  the engineering strain is the change in specimen length divided by the original length. The constant of proportionality,  $E$ , is a measure of

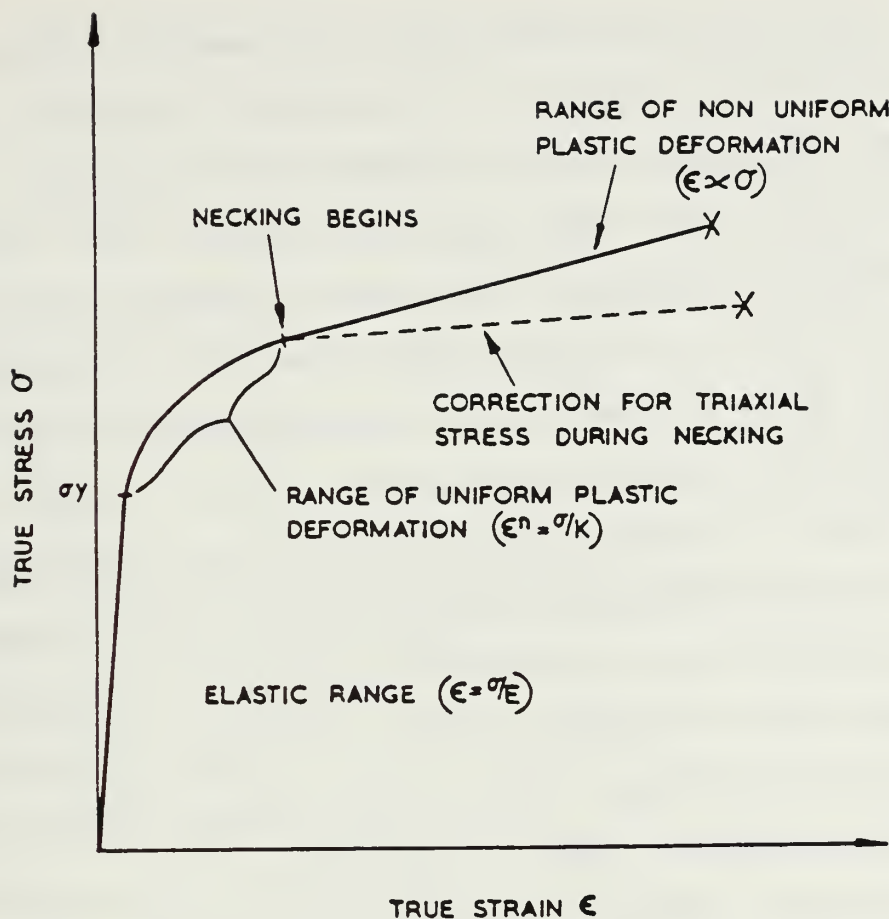


Figure 2. True Stress-True Strain Curve for a Metal without a Pronounced Yield Point

the materials stiffness and is referred to as Young's modulus or the modulus of elasticity. Once the yield stress, generally taken to be the stress necessary to produce 0.2% plastic strain, is exceeded the load necessary to produce further plastic deformation increases. The material is then undergoing strain hardening, by plastic deformation. In this region between the yield stress and the onset of specimen necking stress has been related to strain by expressions such as the Holloman equation [Ref. 20], as shown in Figure



2. The range of nonuniform plastic deformation begins when a localized neck develops in the weakest portion of the specimen. This neck causes a decrease in the specimen cross-sectional area; thus resulting in a decrease in load. The load reaches a maximum at the onset of necking, because the decrease in cross-sectional area offsets the strengthening produced by strain hardening. In this region of the curve the relation between stress and strain becomes more complicated to express mathematically. The development of the neck causes a triaxial stress state to exist instead of uniaxial tension that existed up to the point of necking. In describing the relation between stress and strain in this region the stress resulting from the triaxial stress state must be accounted for. [Ref. 19:pp. 4-21]

In recent years, attention has focused on the development of analytical expressions for stress and strain in the region between the yield stress and the point where necking commences [Ref. 21]. A simple and commonly used expression relating stress and strain for a polycrystalline metal is the Holloman power function [Ref. 20:p. 374].

$$\sigma = K \epsilon^n$$

Where  $\sigma$  is the true stress and  $\epsilon$  the true strain.  $K$  is a constant, representing the true stress at a true strain of unity, called the strength coefficient. When logarithms of

this power function are taken and true stress plotted versus true strain a straight line fit is predicted. The slope of the line has a value of  $n$ , the strain hardening exponent. Conway [Ref. 21: p. 156] notes that, although the equation calls for the use of true strain, "more consistency seems to be observed when true plastic strain is used". In this research the Holloman equation has been tested using the true plastic strain data obtained in testing HSLA- 100.

#### B. INFLUENCE OF TEMPERATURE ON TENSILE PROPERTIES

The strain hardening exponent,  $n$ , is a function of the materials strength level, chemical composition, and microstructure [Ref. 21: p. 157]. A high yield strength is achieved when dislocation motion is impeded initially. Dislocation motion is impeded by obstacles to their movement such as precipitates, impurities and other dislocations. Precipitates and impurities distort an otherwise perfect lattice and set up stress fields on the atomic level. When these stress fields interact with the stress field surrounding a dislocation its motion is impeded. Solid solution and precipitation strengthening are examples of mechanisms which take advantage of these stress field interactions to pin dislocations and thus strengthen a material. In addition to the above mentioned obstacles to dislocation motion, there is an inherent resistance within a crystal lattice to dislocation motion. This resistance is

termed the Peierls force and it is strongly related to the directionality of bonding of the material. A moving dislocation causes bond angle distortions. Covalent and ionic materials are strongly directional in their bonding. The bond angle distortion necessary for dislocation motion in these materials is thus difficult to overcome. In these materials the Peierls force is the primary obstacle to dislocation motion even when lattice vibration energy is enhanced at high temperatures. Body centered cubic materials develop a directional bonding component at low temperatures. The movement of dislocations in body centered cubic materials is thus strongly inhibited at low temperatures by the Peierls force. This effect is nullified at high temperatures where thermally enhanced atomic vibration overcomes the effect of the Peierls force. It is therefore expected that yield strength of HSLA - 100, a body centered cubic material, will exhibit rapidly increasing yield strength with decreasing temperature. An increase in yield strength in this manner will influence the strain hardening exponent. Figure 3 [Ref. 19: p. 33] illustrates this effect for molybdenum a body centered cubic material. [Ref. 22]

### C. INFLUENCE OF STRAIN RATE ON TENSILE PROPERTIES

Strain rate can markedly affect the relationship between stress and strain in a similar way to temperature. In general the strain hardening exponent increases with

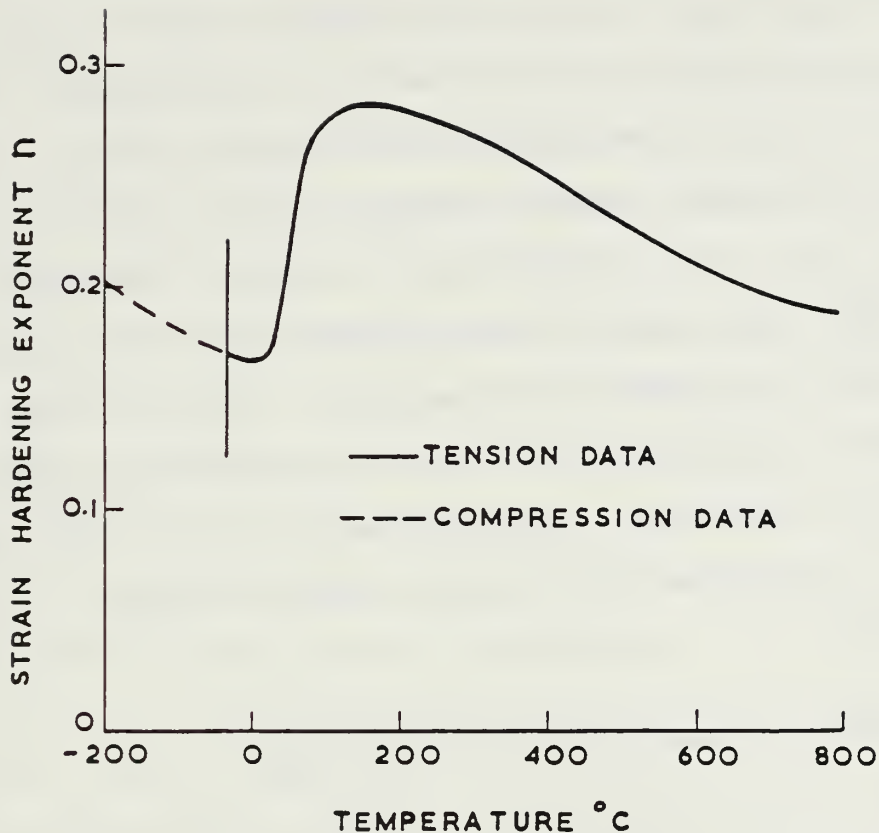


Figure 3. Strain Hardening Exponent of Molybdenum as a Function of Temperature

increasing strain rate [Ref. 21: p. 157]. With conventional tensile testing machines, where a constant loading rate is imposed on specimen, the effect of necking is to increase the strain rate locally. The reduced cross-sectional area in the neck increases the strain and, as the loading is at a constant displacement rate, the strain rate increases. The rate of change of the strain rate continues to increase as the cross-sectional area decreases throughout the test. Tegart states that "the problems associated with necking are

accentuated at high testing speeds because adiabatic heating becomes localized in the necked region" [Ref. 19:pp. 37-38]. The experimental approach used in this research allows a tensile test to be conducted at constant strain rate. The rate of specimen diameter change, a direct measure of strain rate, is the controlling variable. Hourglass shaped specimens are used to ensure necking occurs at the minimum diameter. A diametral extensometer, fitted to the minimum diameter, continually follows the minimum specimen cross-section, providing feedback to the controlling system in order to maintain the constant rate of change of specimen diameter.

#### D. SCOPE AND OBJECTIVES OF PRESENT WORK

The nominal composition for HSLA - 100 steel is listed in Appendix A. Increased amounts of copper, nickel and manganese over that in the currently certified Navy steel HSLA - 80 provide the desired increase in yield strength, but before using this material in Naval ship construction, the resistance to brittle fracture must be evaluated and understood. Existing models for cleavage fracture of steels use the ever present iron carbides as crack initiation sites. However, the low carbon content (0.04%) of HSLA - 100 necessitates research to develop an applicable model. [Ref. 23]



Three regions of fracture behavior, ductile, transition and brittle, occur in steels [Ref. 23]. The terms ductile and brittle describe the amount of plastic deformation occurring at the tip of a crack propagating in a the steel. Ductile behavior, resulting from the nucleation, growth and coalescence of microvoids, is characterized by significant levels of plastic deformation ahead of the crack tip. In a brittle fracture very little plastic deformation at the crack tip is evidenced. In the tensile testing of steels, ductile behavior is observed above a certain critical temperature, and cleavage, primarily a brittle process, is observed below the critical temperature. The critical temperature is termed the Ductile to Brittle Transition Temperature (DBTT). [Ref. 25]

The transition from ductile to brittle fracture behavior occurs over a range of temperature in which the fracture is neither completely ductile nor completely brittle. As a ductile failure is normally preceded by pronounced yielding it is desirable to have a low transition temperature. This precludes failure in a brittle manner, where cracks can propagate catastrophically. As strength levels in a metal are raised, by various means, there is a corresponding loss in the materials ductility. The loss of ductility leads to the fracture mode transition from ductile to brittle. Thus as strength increases, the DBTT for a given metal usually increases.

The DBTT for a particular steel is dependent on factors such as the chemical composition, microstructure, and crystal structure of the steel, as well as the temperature, state of stress, and strain rate at which it is tested. The chemical composition, effects of microalloying additions, and microstructure of HSLA - 100 are discussed with an emphasis on strengthening in the introduction to this work. With respect to DBTT, the effects of individual alloying elements is difficult to evaluate. However, in general nickel is observed to improve toughness and lower DBTT in steels containing less than 0.40% carbon. Interstitial atoms such as carbon and nitrogen can pin dislocations thereby increasing yield strength. Increasing the amount of these atoms present produces a loss of ductility and an increase in DBTT. The effect of the Peierls force on the yield strength of body centered cubic materials as temperature is decreased is discussed above. The increased yield strength of body centered cubic metals at low temperatures causes ductile to brittle transition. When the stress necessary to cause dislocation motion exceeds that for cleavage, brittle fracture results. Similarly, increasing the strain rate promotes brittle fracture because materials which exhibit a strongly increasing yield strength with decreasing temperature also exhibit an increasing yield strength with increasing strain rate [Ref. 22:pp. 211-214]. In order to remove the effect of increasing strain rate on

DBTT, the tensile tests in this research were conducted at constant strain rates as discussed previously. [Ref. 26]

The first phase in the fracture model development is to examine the quasi-static fracture behavior of HSLA - 100 steel. The objective of the present work is to develop the true stress - true strain tensile curves as a function of temperature. This information will be later used in a finite element analysis of the crack tip fracture behavior of this material.

### III. EXPERIMENTAL PROCEDURE

#### A. MATERIAL

Appendix A lists the interim material specifications for trial commercial production of HSLA - 100 steel plates. A 32mm (1-1/4 inch) thick plate of HSLA - 100 steel (Plate # 5644-16B) meeting these specifications was prepared by the supplier. The plate was provided to the Naval Postgraduate School for examination by David Taylor Naval Ship Research and Development Center. The plate was heat treated by the supplier by austenitizing at 949 C (1650 F) for 70 minutes and water quenched; and subsequently aged at 615 C (1050 F) for 70 minutes and water quenched. This resulted in the strength properties reported in Table I, according to the supplier.

TABLE I

STRENGTH PROPERTIES OF PLATE # 5644-16B (AS REPORTED BY THE SUPPLIER)

	Yield Strength (Ksi)	Ultimate Tensile Strength (Ksi)	% Elongation	% Reduction in area
Top Transverse	101	147	22	65
Bottom Transverse	106	139	23	65

## B. TEST APPARATUS

In this research tensile tests were conducted with a Material Test System (MTS) 810 apparatus. On this system the loading is provided via a hydraulic actuator and grip assembly to a threaded specimen receptacle. A diametral extensometer was used to measure diametral displacement which was used as the test controlling variable. Load cell and extensometer output voltages were monitored by a digital voltmeter. The output voltages are converted to load and diametral displacement by a computer program. The computer program for collection of output data is listed in Appendix C. The frequency of sampling the output voltages by the digital voltmeter is determined by the collection program. If the user selects no additional delay between samplings the voltmeter is triggered by the computer to sample the output voltages from the MTS 810 at approximately 4 samplings per second. Thus when monitoring load, diametral displacement and hydraulic actuator piston stroke, all three channels from the MTS 810 can be sampled at least once a second. The program allows the flexibility to input an additional delay between samplings. In the testing conducted for this research no additional delay was requested for the first 50 samplings on all tests. In the intervals between 51 to 200, 201 to 400, and 410 to 500 nominal sampling delays were zero, 1 and 5 seconds respectively. The equipment used to conduct the tensile tests, collect, reduce and display



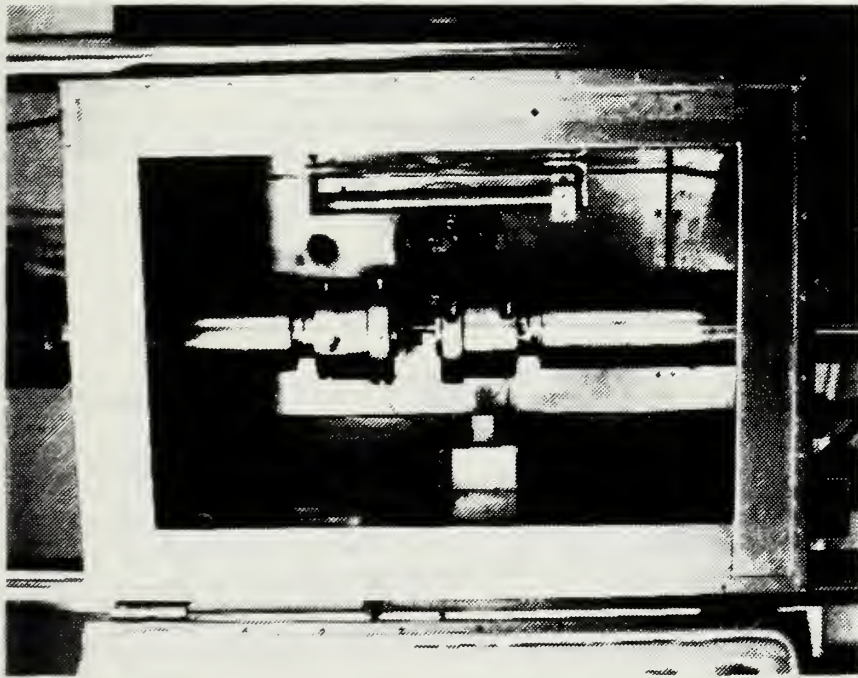
the output data are as follows:

1. MTS Closed-loop Electrohydraulic Testing System
  - a) MTS Model 312.41 Load Frame
  - b) MTS Model 661.21A -O3 Load Cell (25 Kip)
  - c) MTS Model 410.31 Function Generator
  - d) MTS Model 506.20 Hydraulic Power Supply
2. MTS Model 651.1XA Enviromental Chamber (Modified)
  - a) MTS Model 409 Temperature Controller
  - b) MTS Diametral Extensometer Model 632.19B-21 (Modified)
  - c) MTS Extensometer Model 613.20B
3. Hewlitt-Packard Data Acquisition System
  - a) 9826 Computer
  - b) 3497A Data Acquisition Control Unit (DVM)
  - c) 3437A System Voltmeter
  - d) 2617G Printer
  - e) 7225B Plotter

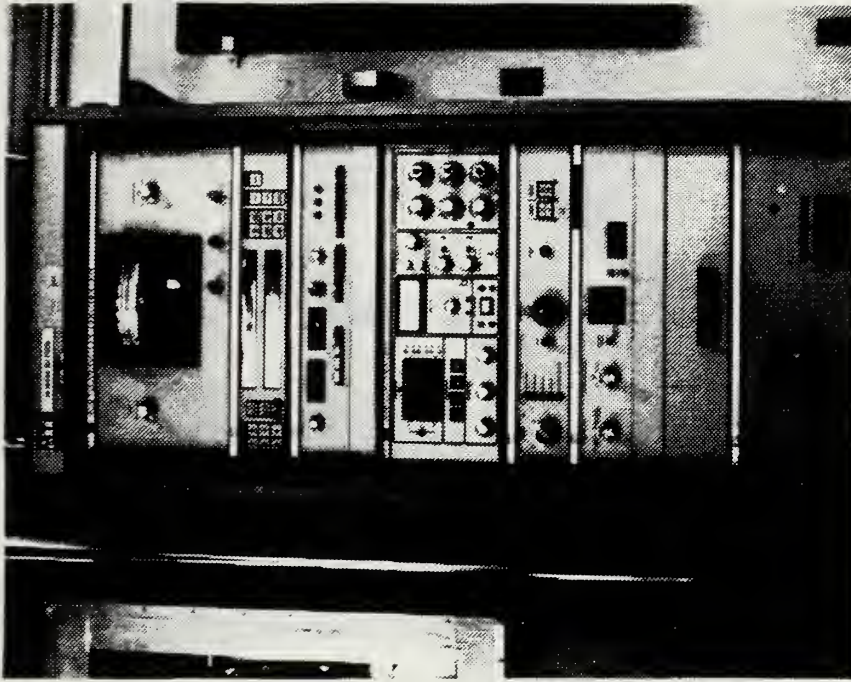
Figures 4a and 4b, are photographs of the testing system and Figure 5 is a photograph of the acquisition and reduction system used in this research. Figure 6 illustrates the enviromental chamber as modified. The enviromental chamber was modified to allow either liquid carbon-dioxide or liquid nitrogen to be used as the cooling medium. An operators checklist and a detailed operational sequence to conduct constant strain rate tensile test are listed in Appendix B.

### C. SAMPLE PREPARATION

The plate, once received at the Naval Postgraduate School was cut and machined into tensile test specimens. Two uniform gage-length specimens were made in accordance with



(a)



(b)

Figure 4. Experimental Test Equipment (a). Environmental Chamber Mounted on Load Frame, with an hourglass Specimen Installed in Hydraulic Actuator Grips (b). MTS 810 Electronic Equipment Console

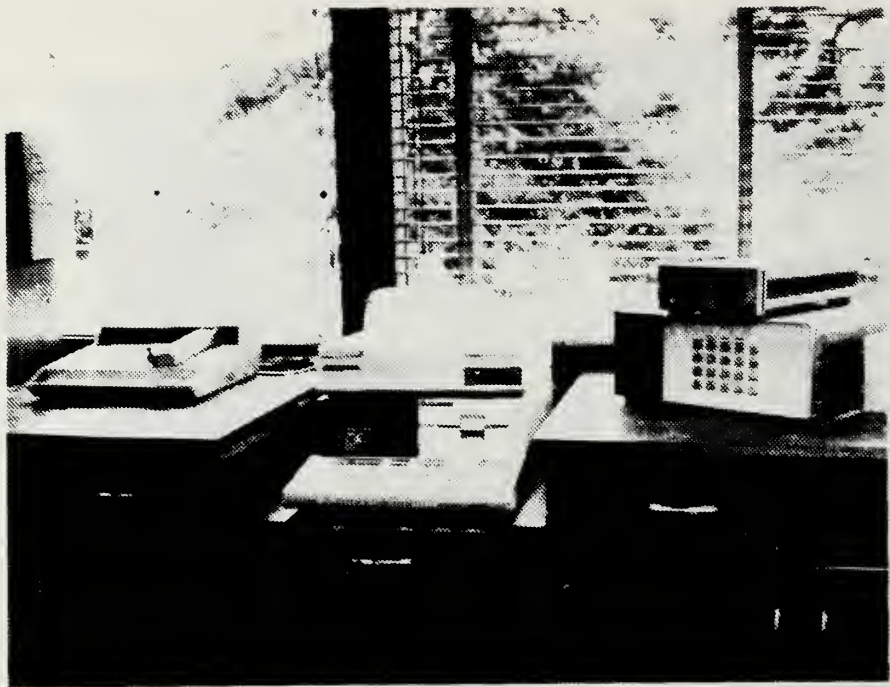
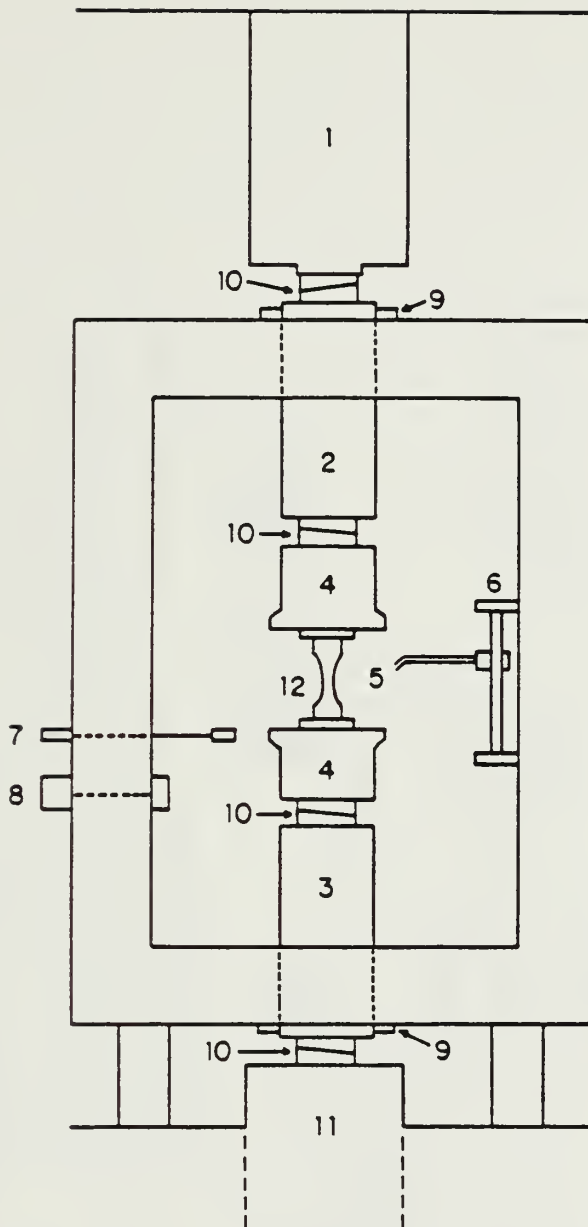


Figure 5. Hewlett Packard 9826 Computer and Data Acquisition System

Figure 7. Twelve hourglass shaped specimens were made in accordance with Figure 8. The samples were cut from the plate parallel to the rolling ( longitudinal ) direction in all cases to ensure the consistency of the results. The hourglass specimen design was selected to ensure that fracture occurred at the minimum specimen diameter where the strain is measured continuously from test start to fracture by using a diametral extensometer. The data thus obtained could then be used to determine the appropriate constitutive equation for this material as a function of temperature.



- |                            |                                     |
|----------------------------|-------------------------------------|
| 1 - 25 KIP Load Cell       | 7 - Extensometer Electrical Hook-up |
| 2 - Load Cell Extension    | 8 - Thermal Couple Junction Box     |
| 3 - Actuator Extension     | 9 - Seal                            |
| 4 - Thermol Hydraulic Grip | 10 - Spiral Washers                 |
| 5 - Diametral Extensometer | 11 - Actuator                       |
| 6 - Extensometer Mount     | 12 - Hourglass Specimen             |

Figure 6. Enviromental Chamber, as Modified

- NOTES: 1. All dimensions in inches.
2. Tolerances as per ASTM tensile specimen standards.
3. Specimen gage length to be parallel to plate as rolled direction.
4. Gage length shall be 32 rms.
5. Mark with applicable specimen number on both ends.

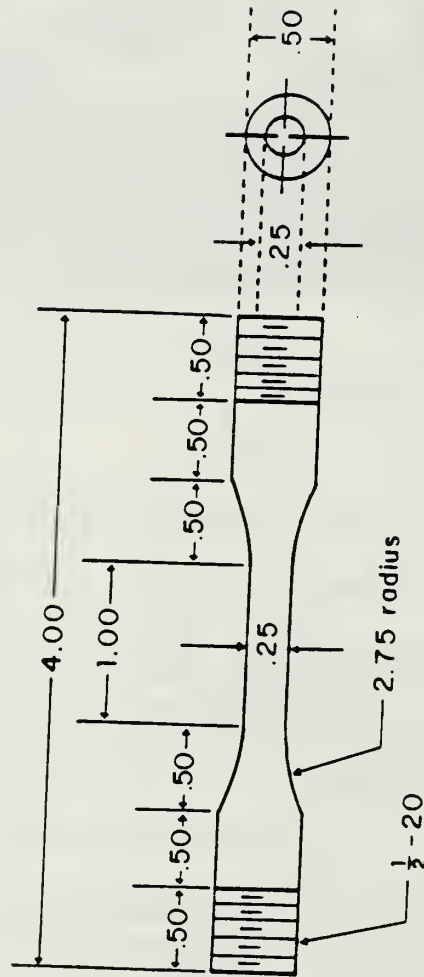


Figure 7. Uniform Gage-length Tensile Specimen Dimensions



- NOTES:
1. All dimensions in inches.
  2. Tolerances: As per ASTM tensile specimen standards.
  3. Specimen gage length to be parallel to plate as rolled direction.
  4. Reduced section area of specimen shall be polished in a manner parallel to specimen longitudinal axis to 32 rms.
  5. Mark with applicable specimen number on both ends, vibrating type engraving tool is permissible.

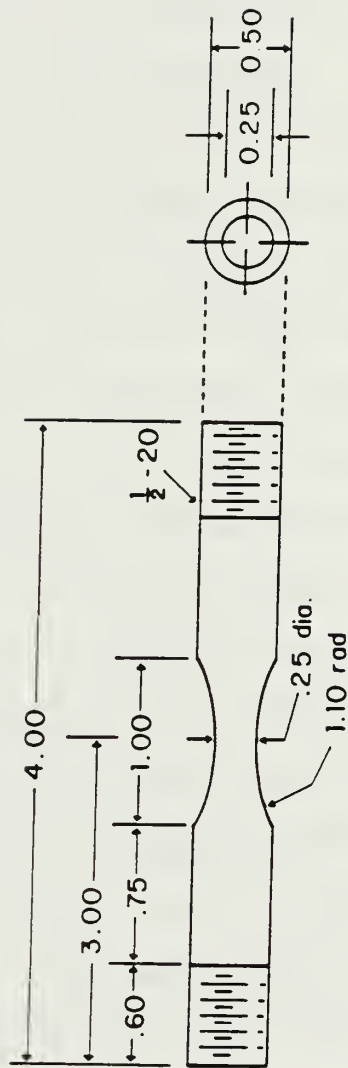


Figure 8. Hourglass Tensile Specimen Dimensions

#### D. COLLECTION, REDUCTION AND DISPLAY OF THE OUTPUT DATA

During a test, data is collected by the acquisition system using the program "JHCOLLECT", Appendix C lists this program. Upon completion of a tensile test the program allows the renaming of data files. The data files are generic in nature and are renamed after each test run with an appropriate specimen number, i.e. lod1, Dia1 etc. Appendix D lists the data reduction program "JHREDUCE". Running this program computes true strain/strain, log true stress/log true strain, corrected true stress/strain, plastic strain, log corrected true stress/true plastic strain and stores these values in arrays. The array names match the specimen numbers i.e. Stress1, Strain1. Appendix E lists the plotting program "JHPLOT". Running this program allows graphs of the array values stored by "JHCOLLECT" and "JHREDUCE". Appendix F lists the program "POWERFIT". Running this program plots the log corrected true stress vs the log plastic true strain from the stored array values. Additionally, the strength coefficient,  $K$ , and strain hardening exponent,  $n$ , for the Hollomon power function are determined [Ref. 20:pp. 374-375]. Using the computed values of slope  $n$  and intercept  $\log K$  a line is plotted between true plastic strain values of .001 and 1.0. A correlation coefficient,  $R$ , for the power function is determined by the powerfit program using a least squares approximation. The correlation coefficient compares the fit between the log

corrected true stress versus log true plastic strain plot and the line generated using the power law coefficients determined.

#### E. TEMPERATURE MEASUREMENT AND CONTROL

Temperature measurement in this research was accomplished using chromel/alumel thermocouples. Chromel/alumel thermocouples are useful over the temperature range -200 to 1300 C. Their uncalibrated accuracy is + 3 C in the range 0 to 400 C [Ref. 27]. Many thermocouples normally used for high temperature monitoring show a decreasing temperature sensitivity with decreasing temperature. For chromel/alumel thermocouples below approximately -130 C the temperature/voltage relation displays this decreasing sensitivity [Ref. 28]. The use of a known fixed temperature reference junction, near the measured temperature, is used to improve accuracy. Several thermocouples were tested in an ice water bath, zero degrees centigrade, and all indicated 0 C, this verified the calibration of the Newport temperature monitoring device. Additionally, the thermocouples were calibrated at -196 C using liquid nitrogen.

Two chromel/alumel thermocouples per test sample were used in the sub zero tensile tests conducted in this research. The samples were spot welded to the hourglass specimen, Figure 8, approximately 0.35 inches on each side of the specimen minimum diameter.

Low temperature tests were initially carried out using the MTS model 409 temperature controller. The controller activated a solenoid to either admit or stop the flow of liquid nitrogen to the environmental chamber. The controller uses a thermocouple to compare sensed temperature with a manually adjustable setpoint. The coolant flow entered through the back of the chamber, by plastic tubing, and was then directed either on the specimen or the actuator grips. This arrangement was satisfactory for tests in which the lowest temperature achievable was desired. Once the specimen thermocouples were stable, at essentially liquid nitrogen temperature, the tensile tests were conducted while maintaining the flow of coolant to the chamber. This method of cooling the samples was not used for test temperatures between room temperature and liquid nitrogen temperature. In this range the on/off action of the solenoid/controller caused the temperature to vary as the coolant flow pulsed on and off. Additionally, the pulsing of coolant flow on the diametral extensometer produced an error signal from the extensometer which prevented starting the hydraulic system. This is a result of the difference in temperature of the extensometer and that of the liquid nitrogen. To conduct the tensile tests at temperatures below room temperature and above liquid nitrogen temperature the coolant flow system was modified. Figure 9, is a photograph of the inside of the environmental chamber with the modified coolant system in



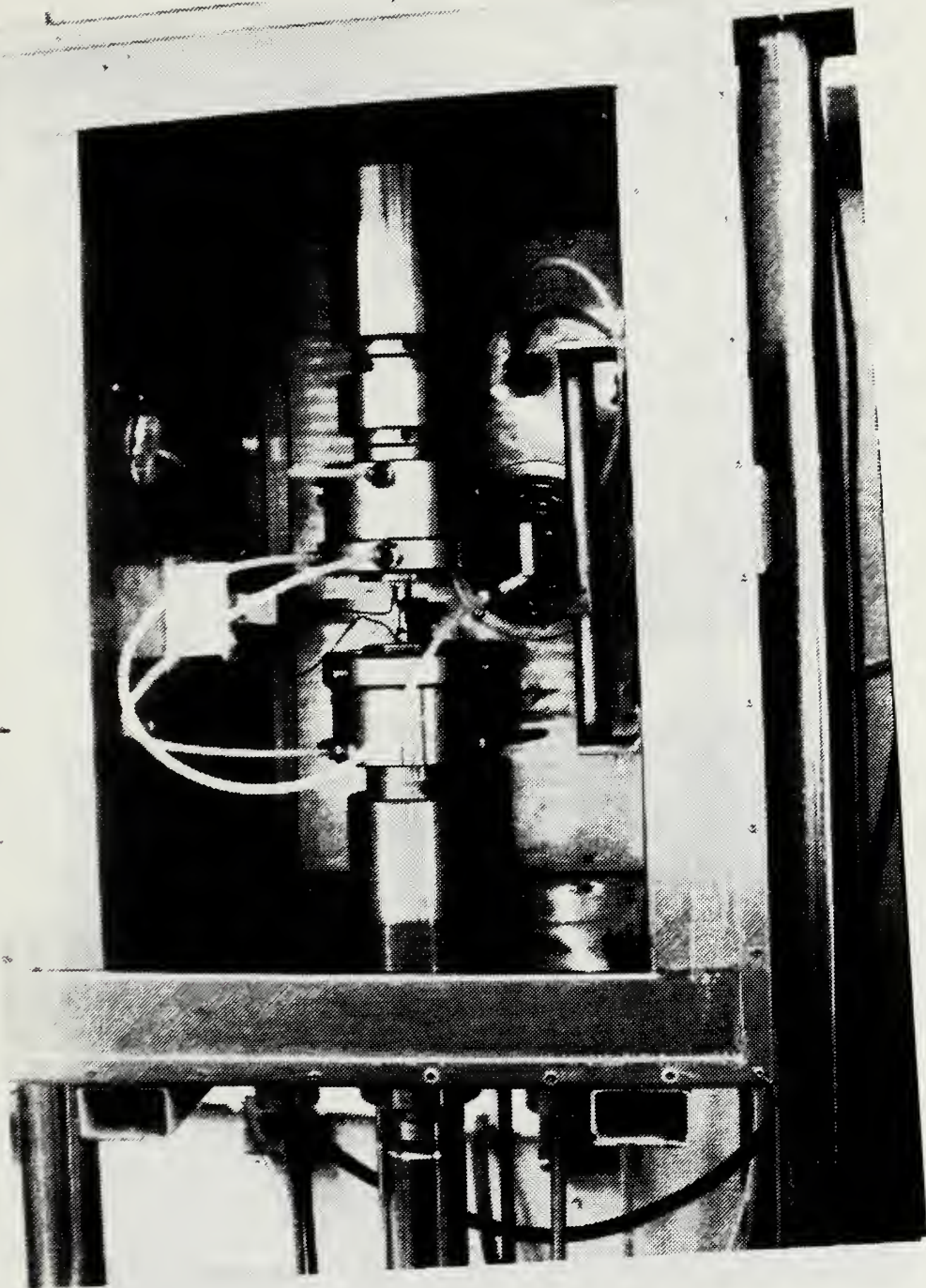


Figure 9. Enviromental Chamber Interior, Showing Modified Coolant System



place. Liquid nitrogen is directed by tubing to machined paths in the actuator grips. Thus, without coolant flow directly on the specimen, the sample is cooled by conduction from the grips to the desired test temperature. Once the temperature has stabilized, the flow of liquid nitrogen to the grips can be stopped and the grips provide a heat sink to maintain the sample at the desired test temperature. The thermocouples were monitored throughout each tensile test; and the average is reported as the test temperature.

## F. MICROSCOPY

### 1. Optical Microscopy

A polished and etched (2% nital) HSLA - 100 sample was photographed using a light microscope. Figure 10 (a) and Figure 10 (b) are representative of the microstructures observed. The microstructure is predominately bainitic and was uniform throughout the thickness of the plate, except for regions of increased grain size near the plate edges.

### 2. Scanning Electron Microscopy

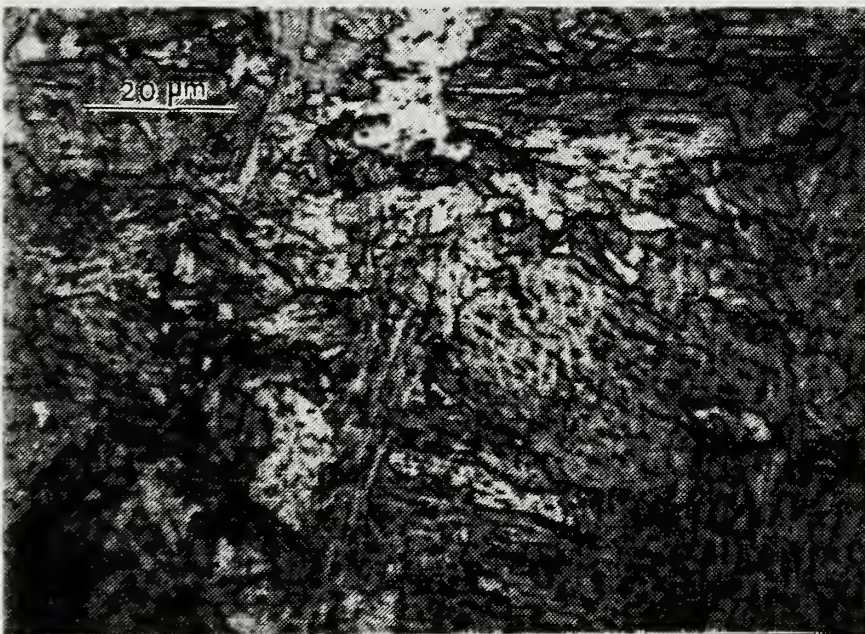
The scanning electron microscope (SEM) was used to examine the HSLA - 100 tensile specimen fracture surfaces after testing. A discussion of the typical fracture surface and micrographs is presented in the results section.

### 3. Transmission Electron Microscopy

Figure 11 is a representative thin foil micrograph of the HSLA - 100 steel used in this research. The



(a)



(b)

Figure 10. Light Micrographs of HSLA - 100 Steel (a). Microstructure at 500X (b). Microstructure at 1000X



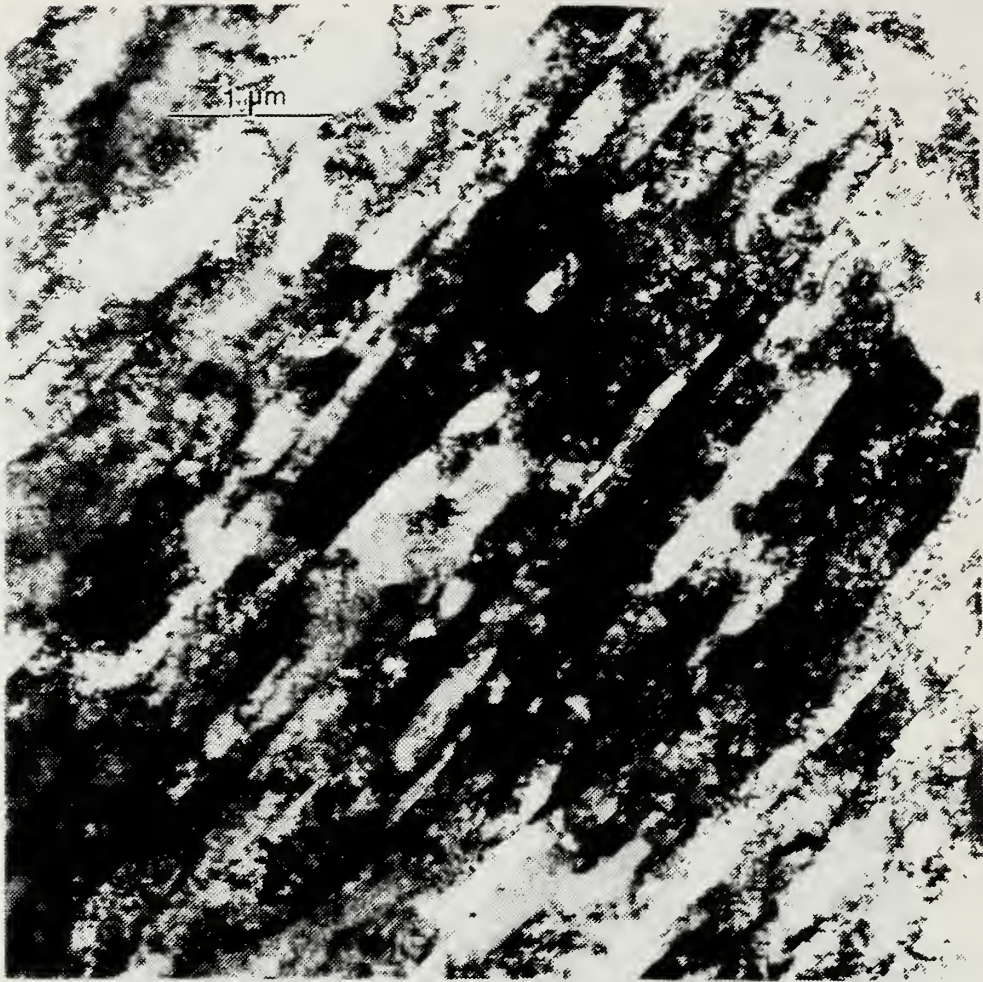


Figure 11. Thin Foil Transmission Electron Micrograph  
of HSLA - 100 Microstructure

microstructure is characterized by elongated parallel laths, less than 1 micron in width, containing a very high dislocation density. In addition, a uniform distribution of very fine niobium carbonitrides was also observed.

#### IV. RESULTS AND DISCUSSION

##### A. MEASUREMENT OF TRUE STRESS

Once a tensile test specimen begins to neck a triaxial stress state exists at the minimum cross-section, Figure 2. In order to obtain the true stress in the specimen a correction for this must be applied to the measured stress. Tegart discusses various expressions for the stress state in the neck but comments that the Bridgman correction most accurately estimates the degree of stress concentration [Ref. 19:pp. 21]. The Bridgman correction can be expressed as [Ref. 29]:

$$\sigma = \frac{\sigma_{av}}{(1 + 2 R/r_n)[\ln(1 + r_n/2R)]}$$

where the measured average stress  $\sigma_{av}$  is reduced to a corrected value  $\sigma$ .  $R$  is the radius of curvature of the neck and  $r_n$  is the radius of the cross-section at the neck.

The initial radius of curvature of the hourglass section of the specimen used in this study is 1.1 in.; this results in an initial correction of  $0.972 \sigma_{av}$ . The objective of this research was to measure true stress and true strain from the onset of loading to the point of fracture. Thus this initial correction has been applied to the true stress up to the onset of necking. Once a test was completed the final radius of curvature was measured by first fitting the specimen

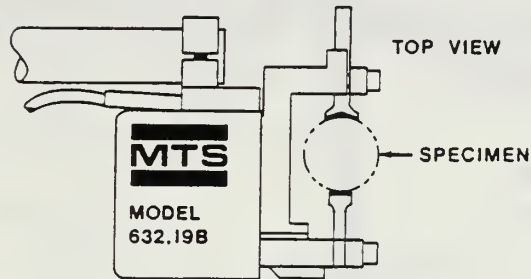
back together and magnifying the necked region with an overhead projector. Then comparing the fit of various circular templates to the projected image produced the final radius of curvature (when divided by the magnification factor). This value along with the measured final cross-section radius allowed determination of a final correction factor for each test specimen. In order to gradually change the magnitude of the Bridgman correction from the onset of necking to fracture, a linear relation was developed between the value at the onset of necking and the fracture point for each specimen. This relation was then applied to the measured true stress values after the maximum load was reached. The justification for using a linearly changing correction factor derived from the fact that the tests were conducted with a constant diametral displacement rate. The computation of the linear relation for the correction factor and its application to individual points is accomplished by the data reduction program, Appendix D.

## B. MEASUREMENT OF TRUE STRAIN

The true strain was determined using an MTS model 632.19B-21 diametral extensometer. Figure 12 shows a typical series 632.19B adjustable diametral extensometer and lists the operating characteristics based on specific model number. The extensometer contacts, shown more clearly in Figures 13 and 14, were not capable of following the



**MODEL 632.19B ADJUSTABLE  
DIAMETRAL EXTENSOMETER**



Model:-	632.19B-20	632.19B-21	632.19B-23
Cage Diameter Adjustment	3,6 mm to 13 mm 0,140 in. to 0,520 in.	3,6 mm to 13 mm 0,140 in. to 0,520 in.	3,6 mm to 13 mm 0,140 in. to 0,520 in.
Maximum Range (Diametral)	$\pm 1,0$ mm $\pm 0,040$ in.	$\pm 1,0$ mm $\pm 0,040$ in.	$\pm 1,0$ mm $\pm 0,040$ in.
Linearity**	0,25% of range	0,25% of range	0,25% of range
Maximum Hysteresis	0,3% of range	0,3% of range	0,3% of range
Temperature Range	-115°F to +250°F	-450°F to +150°F	-450°F to +350°F
Immersibility***	Yes	Yes	Yes
Max Operating Freq with Negligible Distortion	100 Hz	100 Hz	100 Hz
Effective Inertial Mass	45 grams	45 grams	63 grams
Approx Clamp Force on Specimen	250 grams min 325 grams max	250 grams min 325 grams max	250 grams min 325 grams max
Recommended Calibrated Ranges for 10V full scale output from MTS Transducer Conditioner****	$\pm 0,040$ in./ $\pm 1,0$ mm $\pm 0,020$ in./ $\pm 0,5$ mm $\pm 0,008$ in./ $\pm 0,2$ mm $\pm 0,004$ in./ $\pm 0,1$ mm	$\pm 0,040$ in./ $\pm 1,0$ mm $\pm 0,020$ in./ $\pm 0,5$ mm $\pm 0,008$ in./ $\pm 0,2$ mm $\pm 0,004$ in./ $\pm 0,1$ mm	$\pm 0,040$ in./ $\pm 1,0$ mm $\pm 0,020$ in./ $\pm 0,5$ mm $\pm 0,008$ in./ $\pm 0,2$ mm $\pm 0,004$ in./ $\pm 0,1$ mm

\*All models include case, instruction manual, and mating connector (Amphenol 165-14).

\*\*When calibrating over a range from tension to compression, linearity is somewhat degraded; however, this is electronically compensated to the stated value by the recommended MTS Transducer Conditioner modules.

\*\*\*Immersible in most fluids used for specimen heating and cooling, including alcohol, acetone and silicone fluids.

\*\*\*\*Recommended Transducer Conditioners: 440,21, 425,41 (option B), 406 (option A). Other conditioners may be used (maximum excitation is 12v, output is approximately 3mv/v).

**Figure 12. Model 632.19B Diametral Extensometer  
and a Table of Specific Model  
Operating Characteristics**

diametral displacement once necking produced a radius of curvature below .5 inches. The contacts were modified to allow the measurement of strain up to the minimum radius of the neck which preceded fracture. Figure 15 is a photograph of the extensometer contacts after modification. The limited range of accurate unmodified extensometer travel is

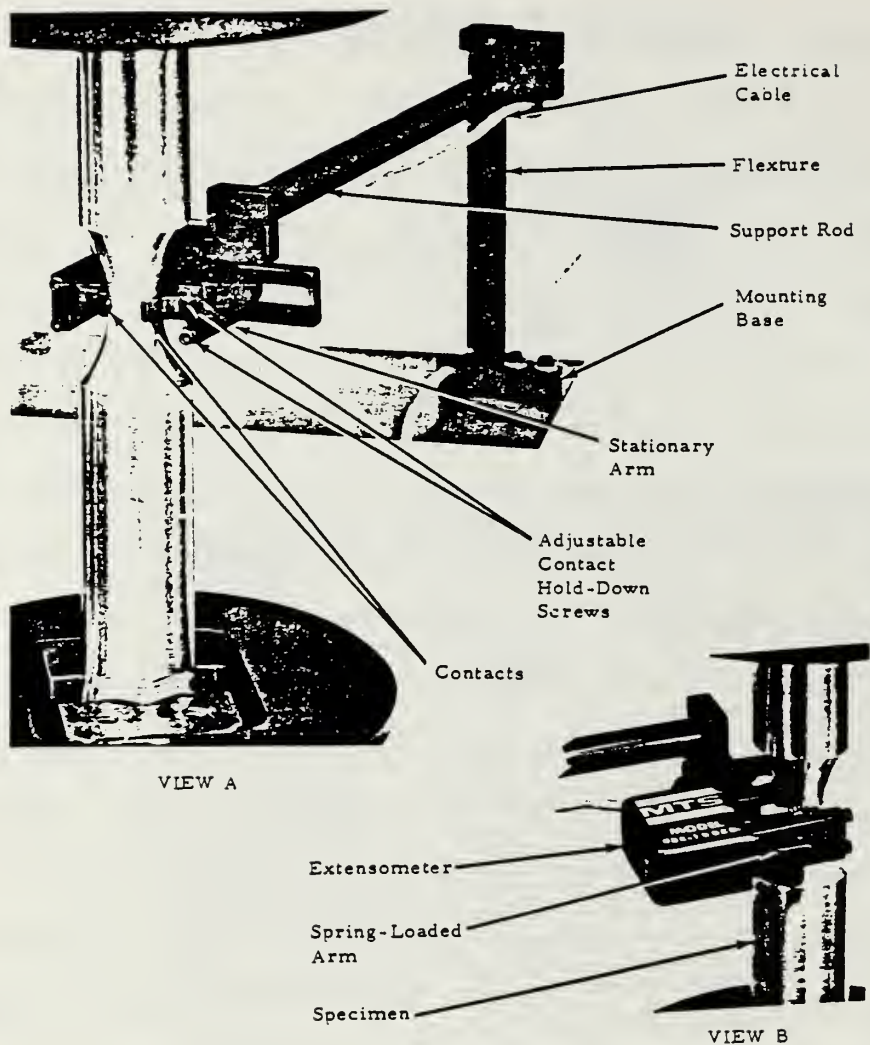


Figure 13. Typical Series 632 Adjustable Diametral Extensometer - Attachment to Specimen

reflected in Figure 16, the load vs. diametral displacement curve for hourglass specimen number 4. Figure 17, the load displacement curve for hourglass specimen number 5, illustrates the improved range of measuring diametral displacement once the extensometer was modified.

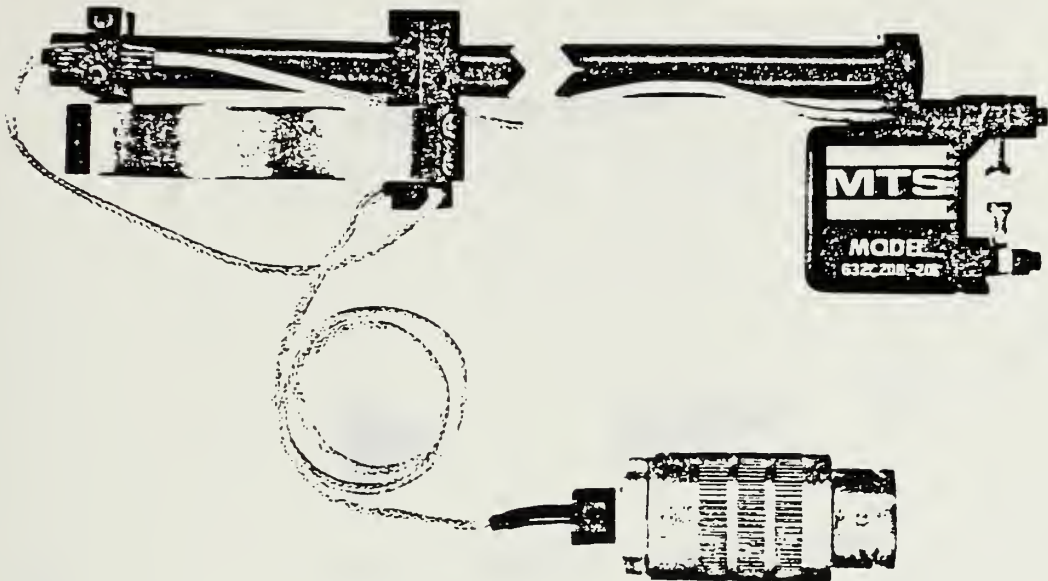
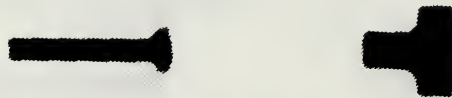
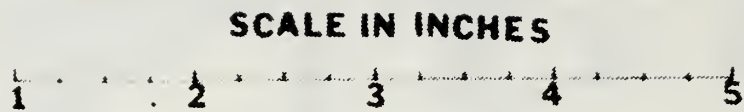


Figure 14. MTS Diametral Extensometer with Mounting Assembly and Electrical Connection

#### C. DETERMINATION OF THE MODULUS OF ELASTICITY

The value of the modulus of elasticity or Young's modulus for the HSLA - 100 steel tested in this research was determined experimentally. The test of hourglass specimen number 4, Figure 16, indicated yielding occurred for loads above approximately 5.5 Kips. A uniform gage-length specimen equipped with an axial extensometer was loaded to 4 Kips in load control at a rate of  $4 \times 10^{-3}$  Kip/sec. The specimen was loaded to 4 Kips then returned to zero load at the same rate. This was done twice and the value of Young's modulus determined by the slope of the stress - strain curve generated by an X - Y recorder. The average value of Young's modulus for the two tests is  $2.414 \times 10^6$  psi. This value was



unmodified contact arms



modified contact arms

Figure 15. Model 632.19B-21 Diametral Extensometer Contacts  
(Unmodified and Modified)

HSLA-100 HOURGLASS  
SPECIMEN NO. 4

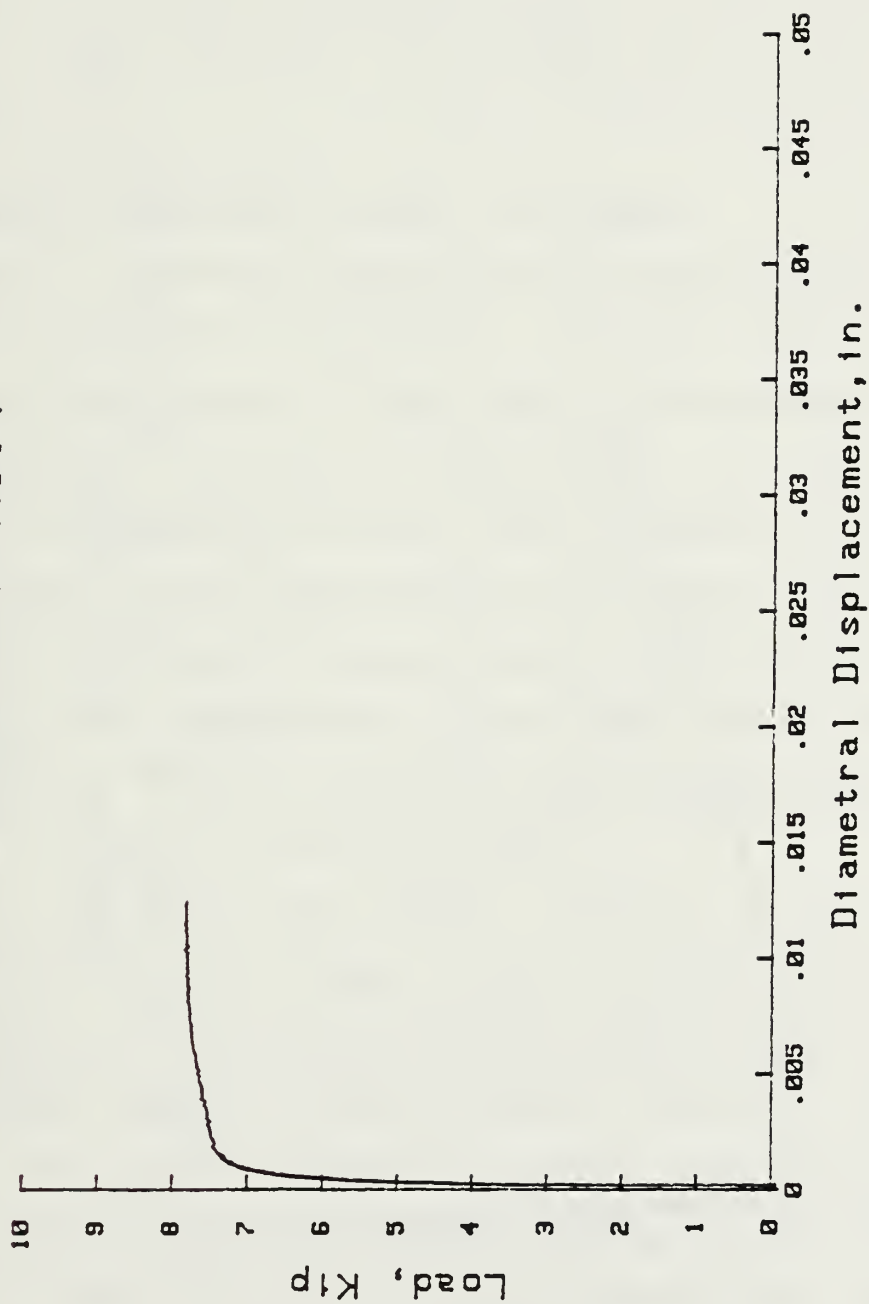


Figure 16. Load - Diametral Displacement Curve for Hourglass Specimen No. 4, Tested at Room Temperature.



# HSLA-100 HOURGLASS SPECIMEN NO.5

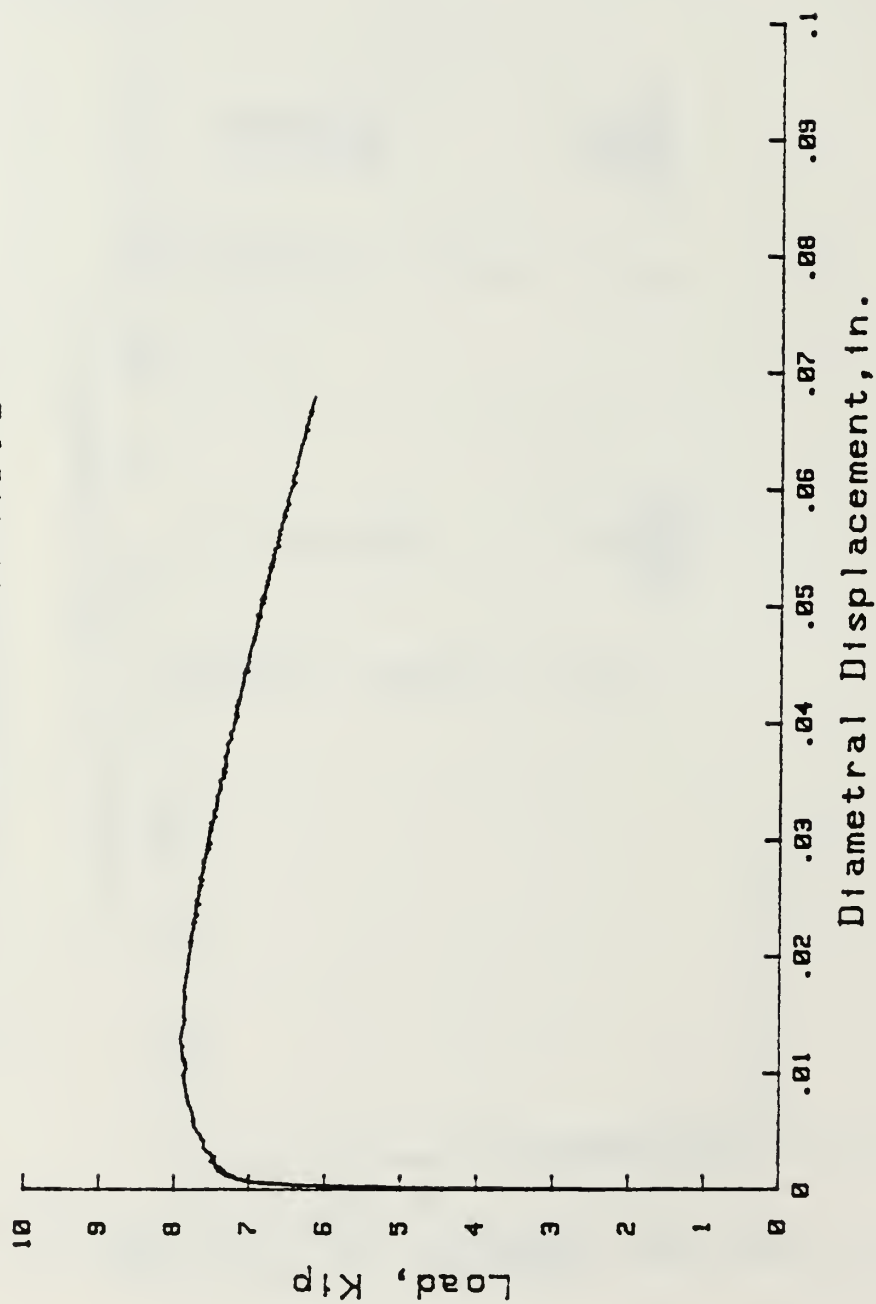


Figure 17. Load - Diametral Displacement Curve for Hourglass Specimen No. 5, Tested at Room Temperature

then used along with the corrected true stress in the determination of the true plastic strain, as follows:

$$\epsilon_p = \epsilon_t - \sigma/E$$

where  $\epsilon_p$  is the true plastic strain,  $\epsilon_t$  the total true strain,  $\sigma$  the corrected true stress and  $E$  is Young's modulus.

#### D. TENSILE PROPERTIES OF HSLA - 100 STEEL

Table II summarizes the mechanical properties for HSLA - 100 resulting from this research. The test temperature for hourglass specimen no. 6 was taken as the average of the test start and test complete temperatures. There was a 36 C change in temperature from test start to specimen failure as the coolant supply exhausted prior to starting the test and prior to the actuator grips/extensions equilibrating at the desired test temperature. In all other tests the test temperature, taken as the start/finish average, varied less than + 10 C from the start to finish.

In comparing the results reported by the plate manufacturer listed in Table II with those obtained in this study Table I, an obvious difference exists. The uniform gage-length samples from this study exhibited comparable values for percent reduction in area (% R/A) and ultimate tensile strengths (UTS) to those reported by the supplier. However, the .2% offset yield strength values are much

higher and the % elongation is much lower than reported by the supplier. The unexpectedly high yield strength results, of the room temperature tensile tests were reported to the project liaison at David Taylor Research and Development

TABLE II

STRENGTH PROPERTIES OF HSLA - 100 PLATE # 5644-16B (AS DETERMINED IN THIS RESEARCH) - HOURGLASS SPECIMEN

No.	Average Test Temperature (deg C)	Yield Strength (ksi)	Ultimate Tensile Strength (ksi)	Elongation in 1 inch (%)	Reduction in Area (%)
1	21	a	a	N/A	63.0
2	21	127.0	156.9	N/A	b
3	20	a	a	N/A	62.7
4	20	126.0	156.7	N/A	59.6
5	24	130.8	156.1	N/A	63.7
6	-109	159.0	177.2	N/A	*48.8
7	-176	184.2	201.2	N/A	27.0
8	-196	a	a	N/A	27.0
9	-72	146.8	164.1	N/A	62.3
10	-27	137.2	159.3	N/A	64.7
11	-150	167.7	184.2	N/A	*54.5
12	-129	156.7	177.0	N/A	*55.9

UNIFORM GAGE-LENGTH SPECIMEN

1	23	132.7	142.6	12.3	68.6
2	22	130.4	142.6	16.4	68.6

a - no data collected.

b - specimen not tested to the point of fracture.

\* - specimen didnot fail at the minimum diameter. The % R/A in the table is based on the specimen minimum diameter and is therefore a conservative (low) value.

Center, Mr. M. Vassilaros. Subsequent conversation with Mr. Vassilaros revealed that the plate received at the Naval Postgraduate School had not been heat treated properly and

that yield strengths above those in the interim HSLA - 100 specification should be expected.

In addition to the load versus diametral displacement curves, as shown in Figures 16 and 17, the reduction and plotting programs, Appendices D and E respectively, allow other useful curves to be generated. The next several figures will provide a sample of the various plots and serve to compare the results at room temperature to a test at - 176 C.

The true stress - true strain curves at room temperature and -176 C are shown in Figures 18 and 19 respectively. Note the marked increase in true stress and corresponding decrease in ductility in the -176 C temperature test. As expected, the strength is higher and ductility lower at -176 C than at room temperature. Figure 20, applies the linearly varying Bridgman corrected true stress to the results shown in Figure 18. The maximum correction to the true stress for the triaxial stresses in the necked region of this sample is 0.955. The maximum travel (0.072) of the diametral extensometer was too small to follow the deformation process to the fracture point, the fracture point is plotted as an asterisk. The decrease in ductility at low temperatures, Figure 21, allowed the extensometer to follow the deformation process to the fracture point. The log true stress-log true strain curves for room temperature and -176 C are shown in Figures 22 and 23. When the true stress is

# HSLA-100 HOURGLASS SPECIMEN NO.5

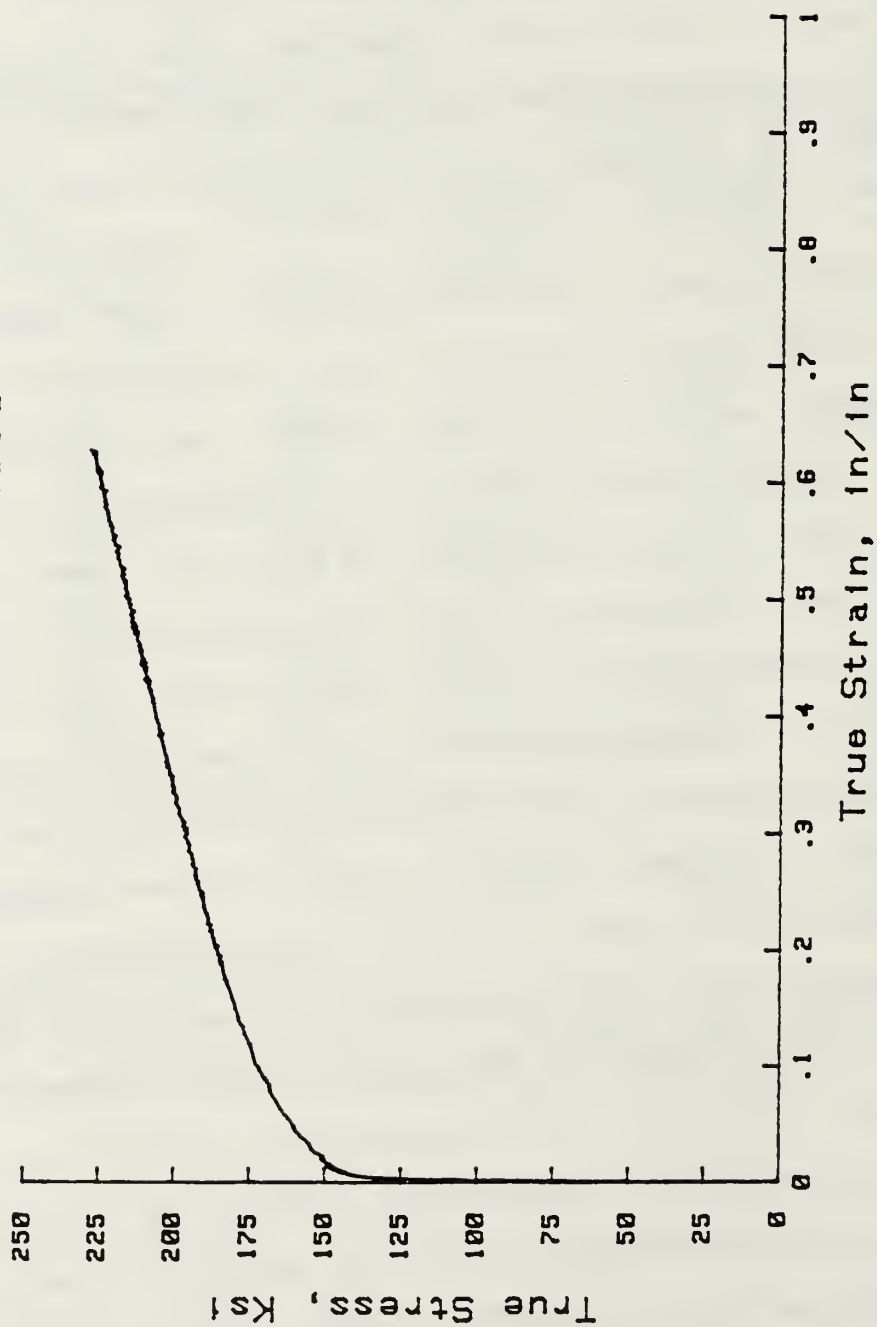


Figure 18. True Stress - True Strain Curve for Hourglass Specimen No. 5, Tested at Room Temperature



# HSLA-100 HOURGLASS SPECIMEN NO.7

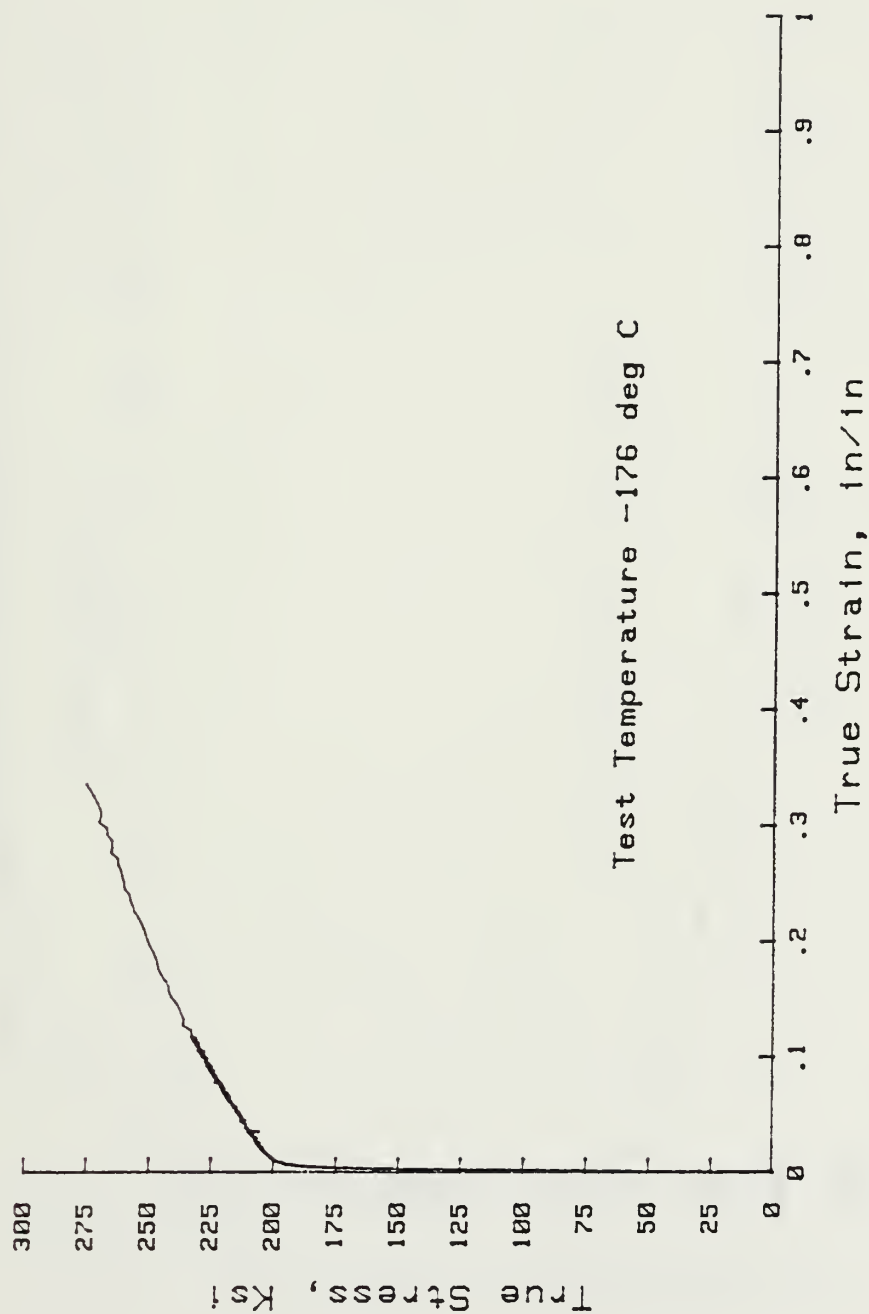


Figure 19. True Stress - True Strain Curve for Hourglass Specimen No. 7, Tested at -176 C

# HSLA-100 HOURGLASS SPECIMEN NO.5

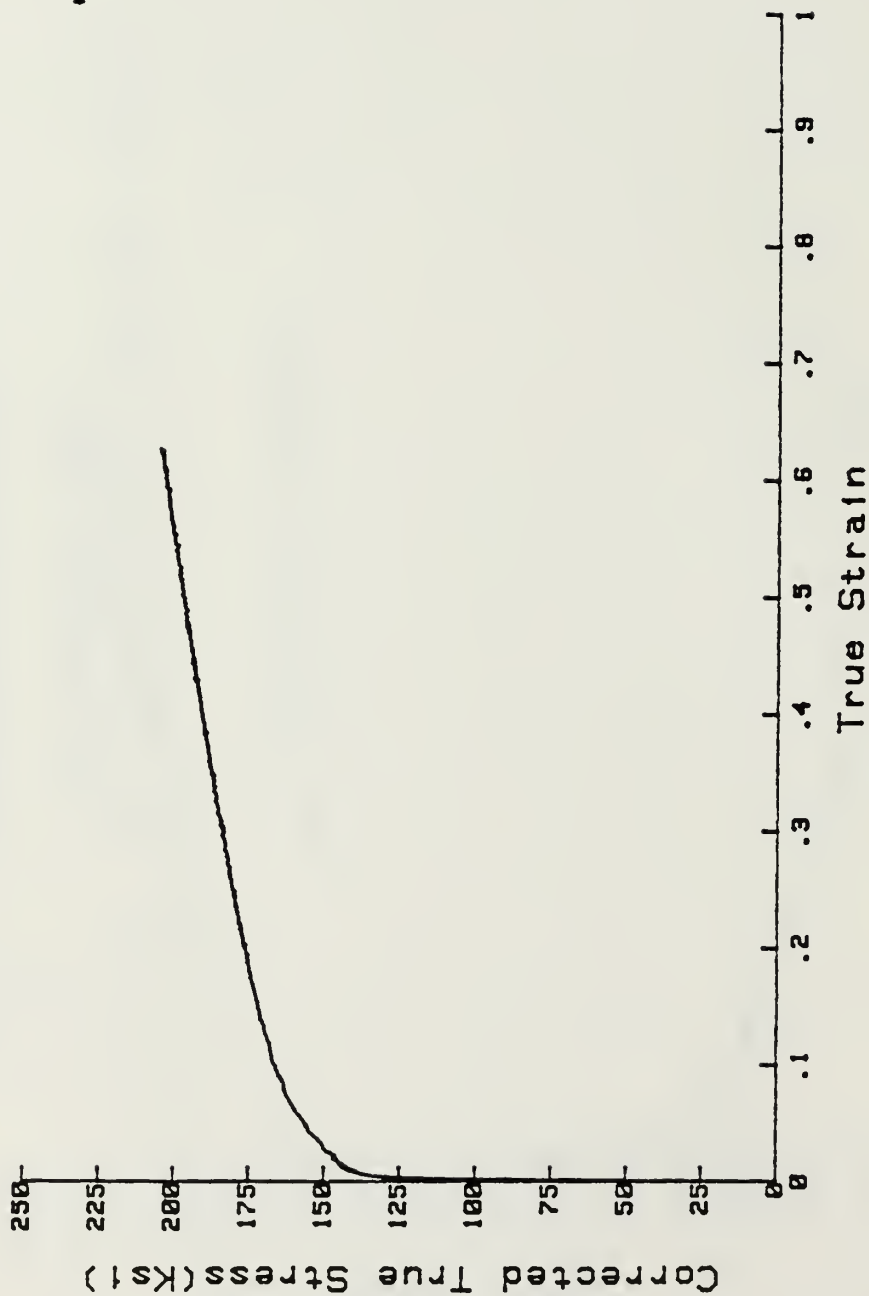


Figure 20. True Stress (Corrected for Necking) - True Strain Curve for Hourglass Specimen No. 5, Tested at Room Temperature, \* Indicates Fracture Point

# HSLA-100 HOURGLASS SPECIMEN NO. 7

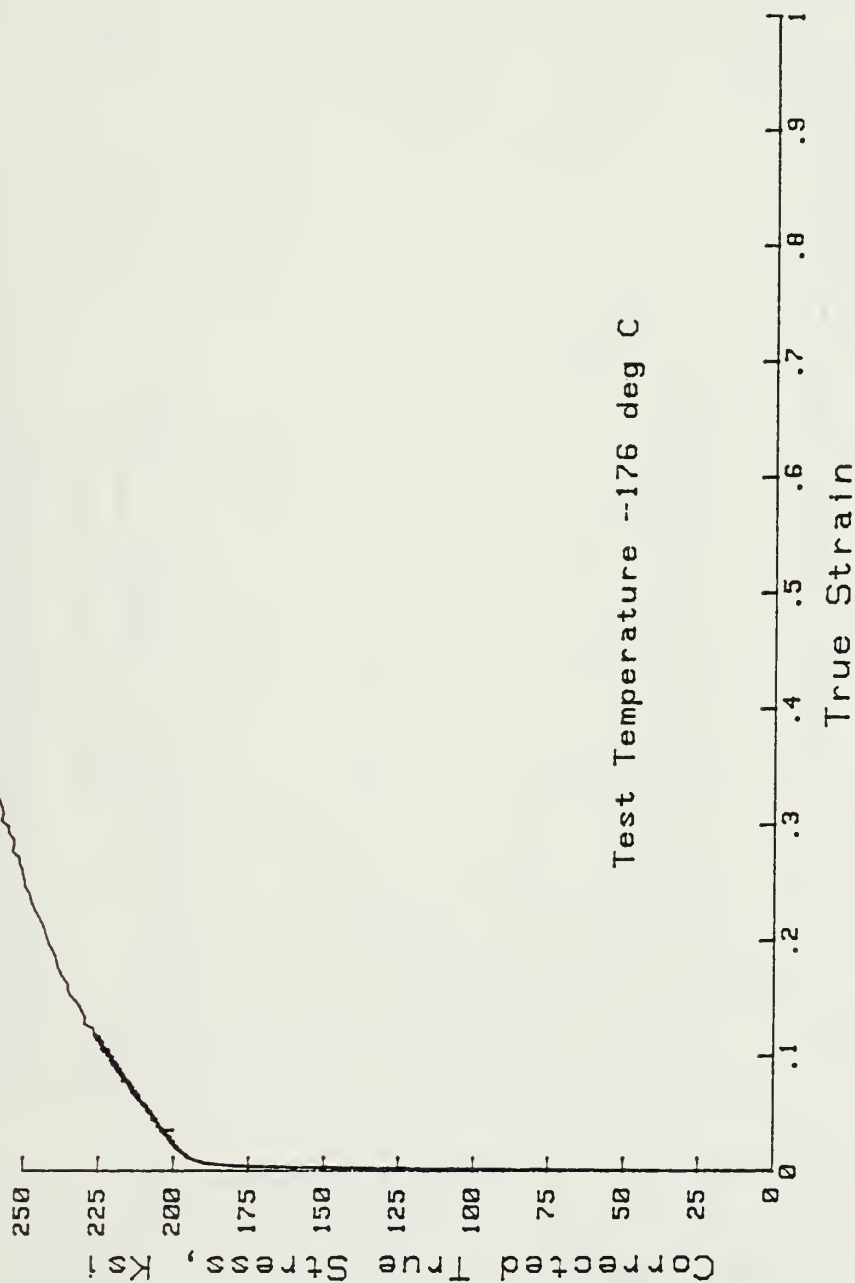


Figure 21. True Stress (Corrected for Necking) - True Strain Curve for Hourglass Specimen No. 7, Tested at -176 C, \* Indicates Fracture Point

# HSLA-100 HOURGLASS SPECIMEN NO.5

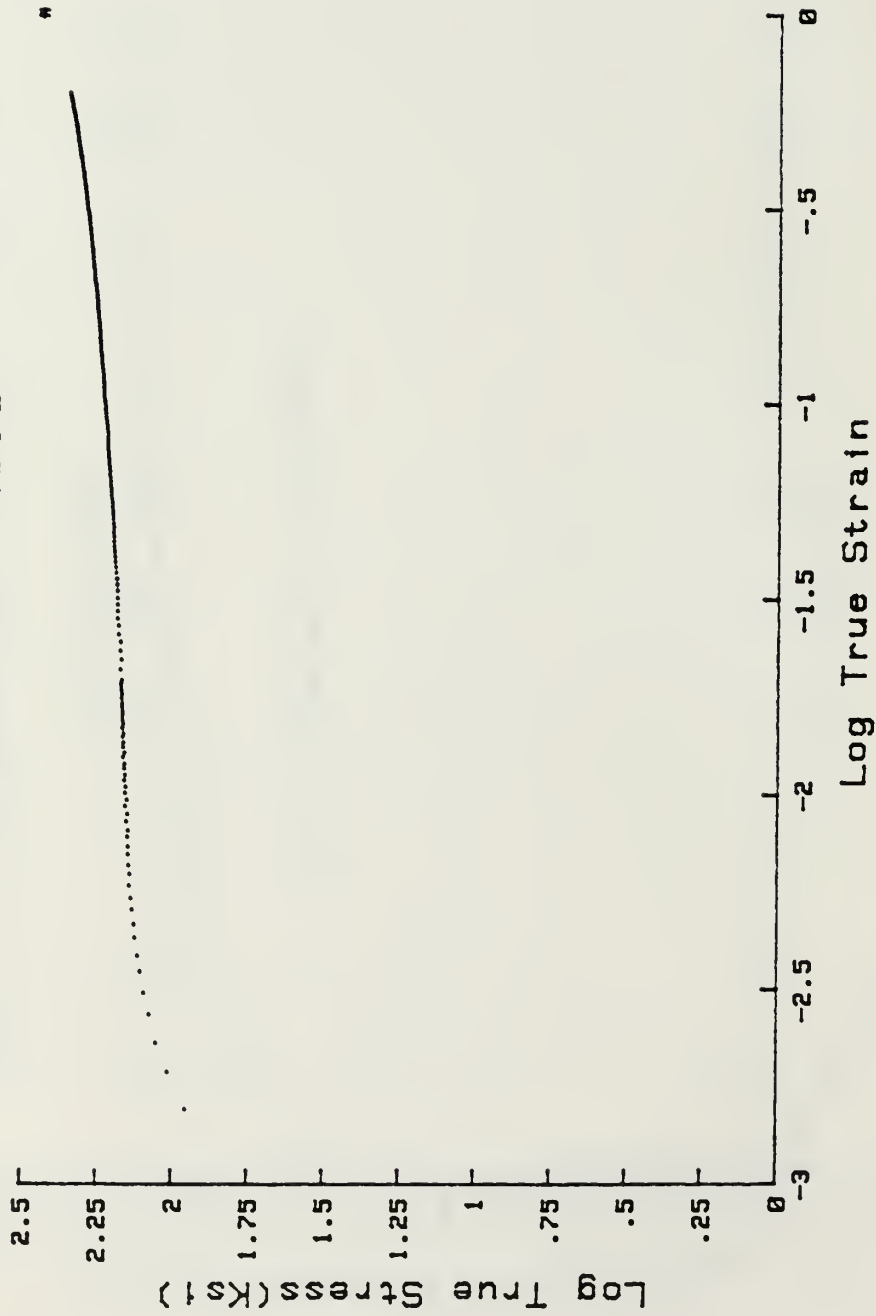


Figure 22. Log True Stress - Log True Strain Curve for Hourglass Specimen No. 5, Tested at Room Temperature, \* Indicates Fracture Point

# HSLA-100 HOURGLASS SPECIMEN NO. 7

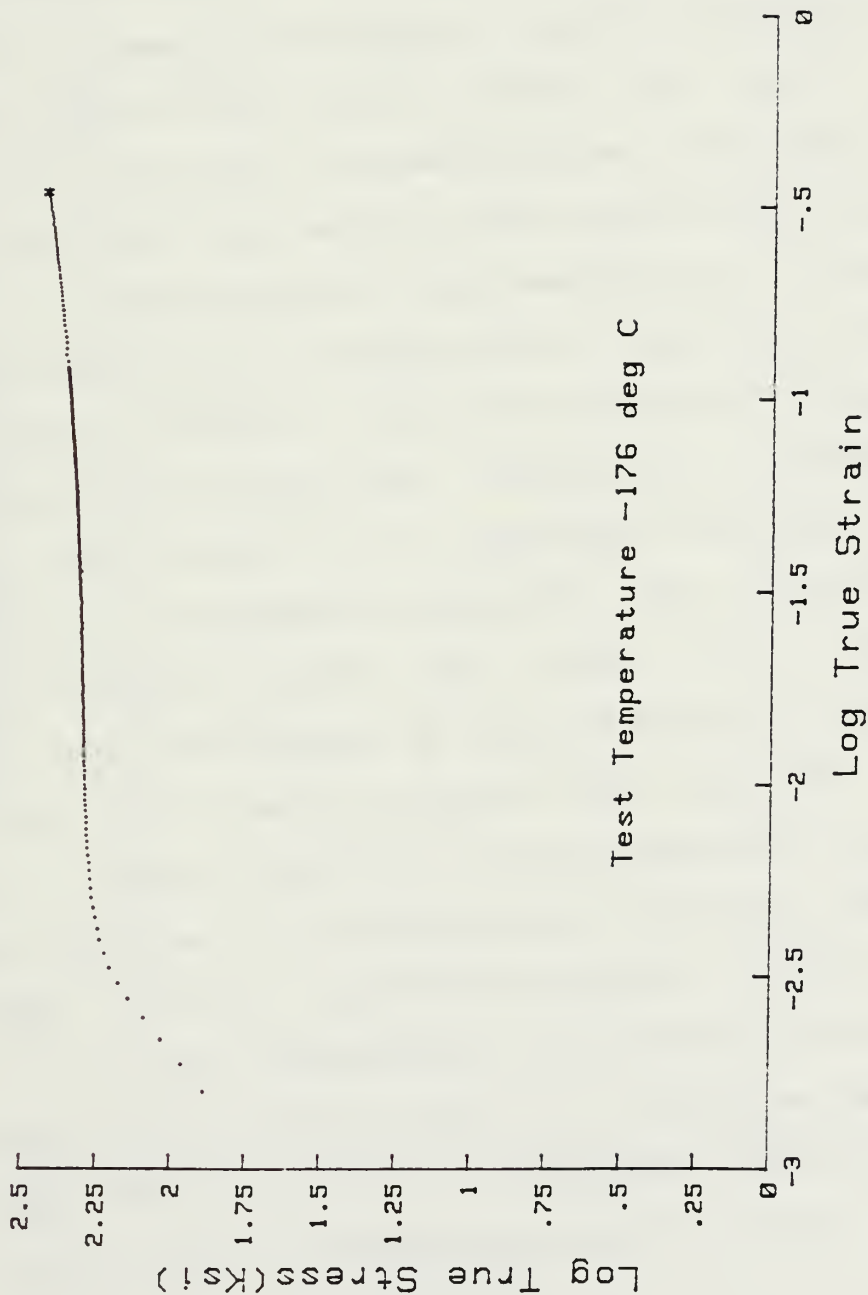


Figure 23. Log True Stress - Log True Strain Curve for Hourglass Specimen No. 7, Tested at -176 C, \* Indicates Fracture Point



corrected for initial specimen geometry and the triaxiality associated with necking the resulting curves, Figures 24 and 25, reflect a lowering of the log true stress values. The reduction in corrected log true stress values over the uncorrected values increases with increasing strain due to the decreasing radius of curvature in the necked area. The log true strain values in Figures 22 through 25 are total true strain. By subtracting the elastic strain from the total true strain an approximately linear true stress - true plastic strain results when plotted logarithmically, Figures 26 and 27; the Holloman power function appears to closely describe the stress - strain behavior of this material.

Figure 28 presents the yield strength of HSLA - 100 as a function of temperature. The rapidly increasing strength with decreasing temperature is a result of the increasing Peierls force with decreasing temperature for this body centered cubic steel. The percent reduction in area undergoes a rapid decrease at temperatures below -150 C, Figure 29. The three results between -100 C and -150 C represent the minimum percent reduction in areas, since the specimens actually failed outside the minimum diameter. These results indicate that HSLA - 100 steel experiences little loss in ductility at temperatures above -150 C. The fact that specimens 6, 11, and 12 failed outside the minimum diameter is most remarkable. In all three cases significant necking, based on % R/A, preceded specimen failure. The

# HSLA-100 HOURGLASS SPECIMEN NO.5

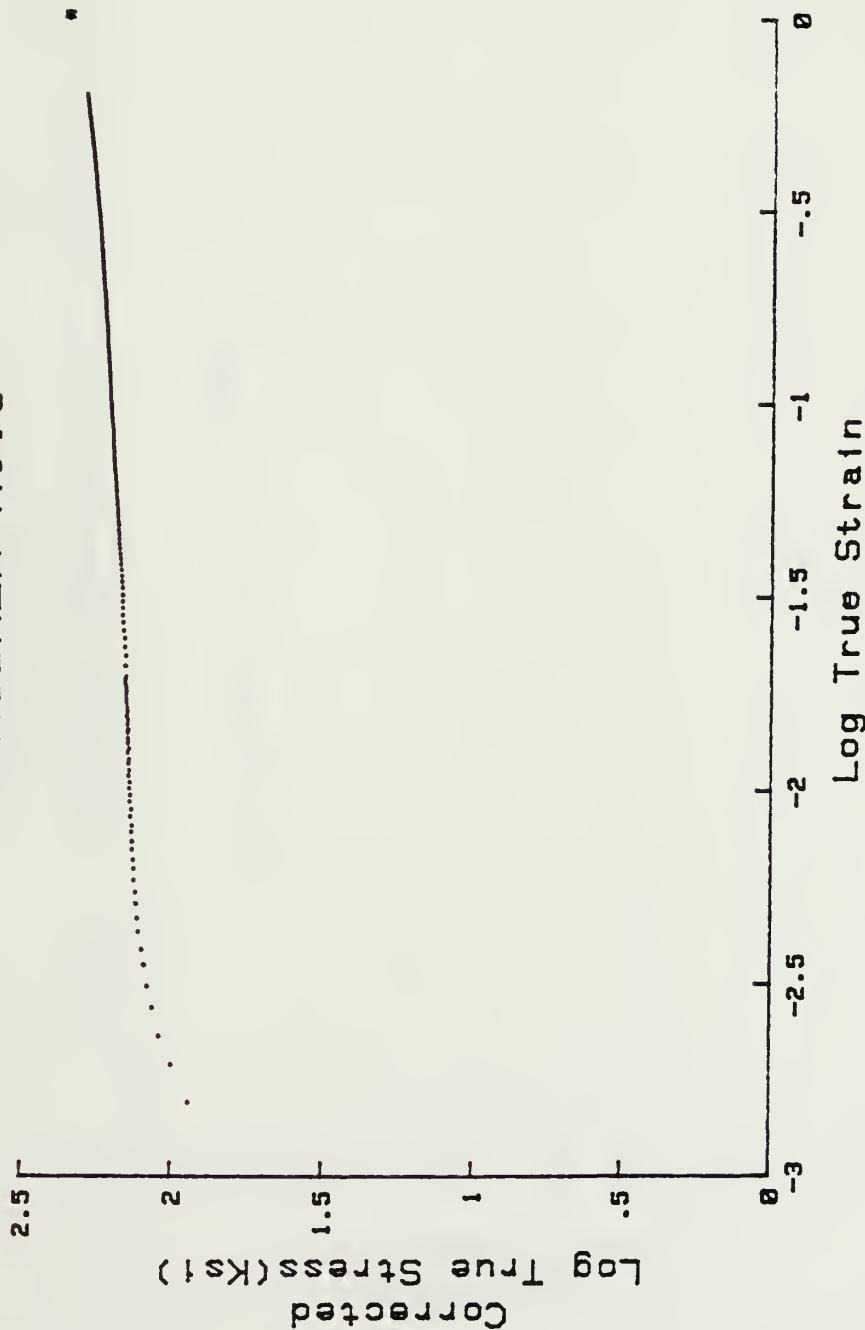


Figure 24. Log True Stress (Corrected for Necking) - Log True Strain Curve for Hourglass Specimen No. 5, Tested at Room Temperature, \* Indicates Fracture Point

# HSLA-100 HOURGLASS SPECIMEN NO.7

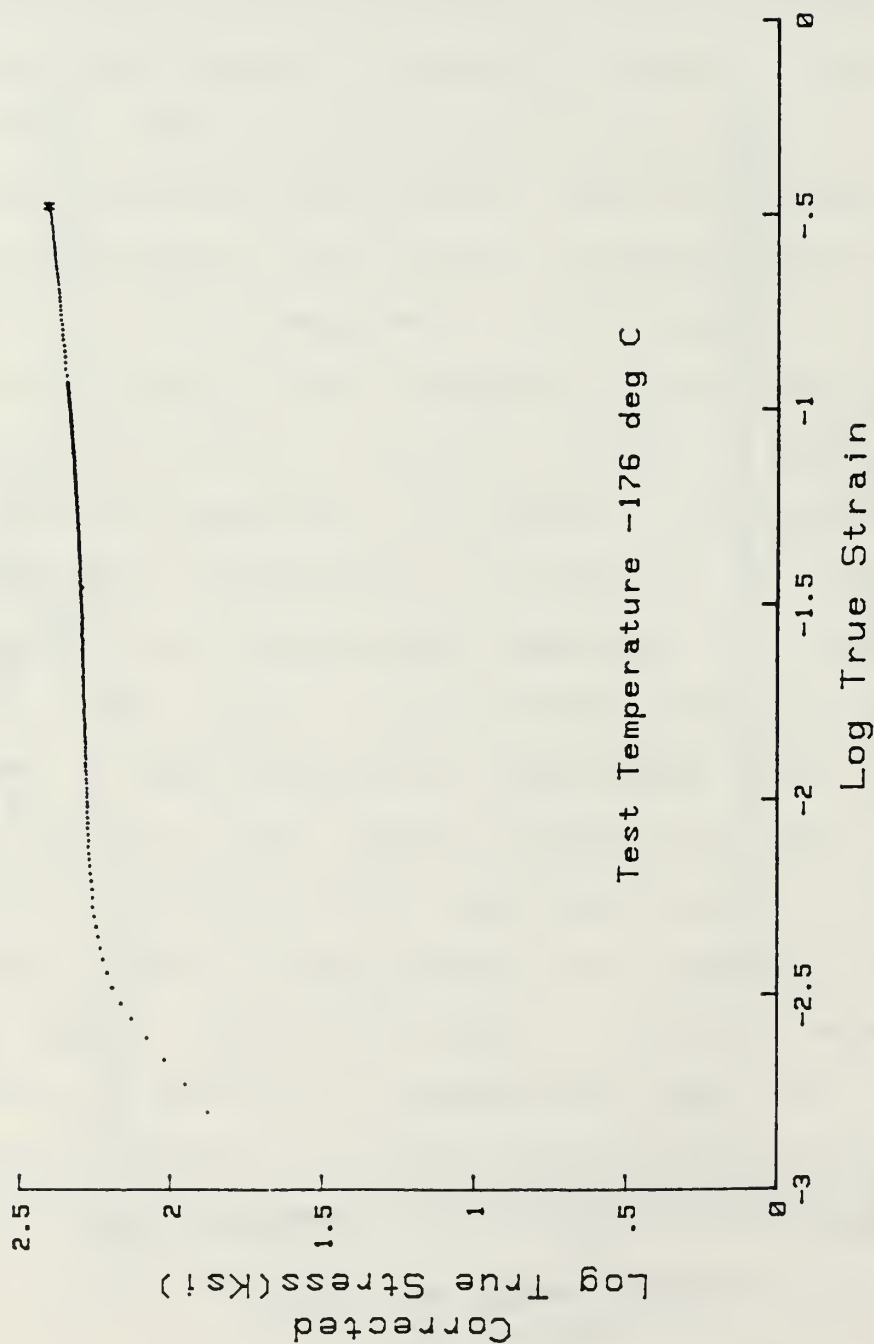


Figure 25. Log True Stress (Corrected for Necking) - Log True Strain Curve for Hourglass Specimen No. 7, Tested at -176 C, \* Indicates Fracture Point

# HSLA-100 HOURGLASS SPECIMEN NO.5

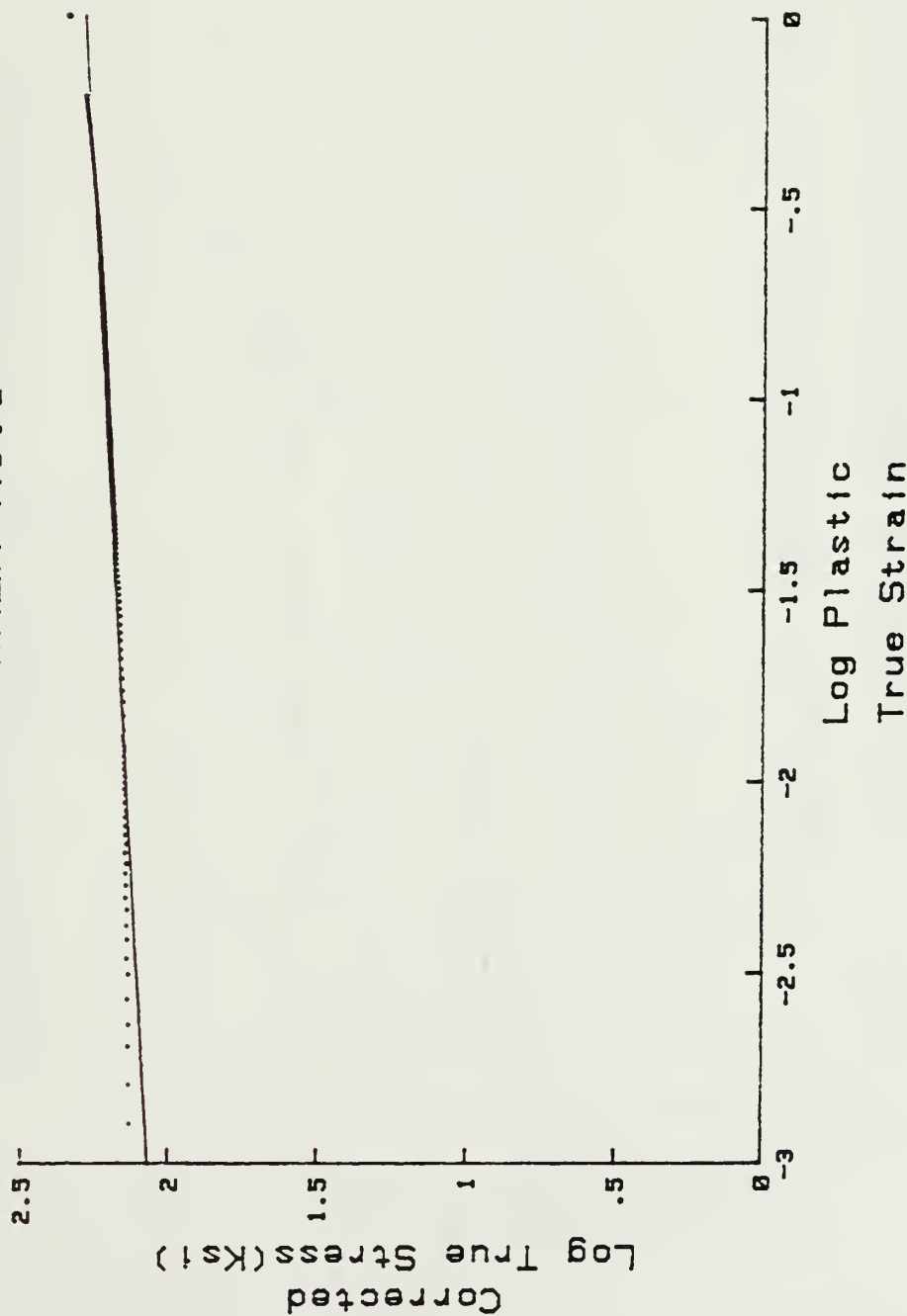


Figure 26. Log True Stress (Corrected for Necking) - Log True Plastic Strain Curve for Hourglass Specimen No. 5, Tested at Room Temperature, \* Indicates Fracture Point

# HSLA-100 HOURGLASS SPECIMEN NO. 7

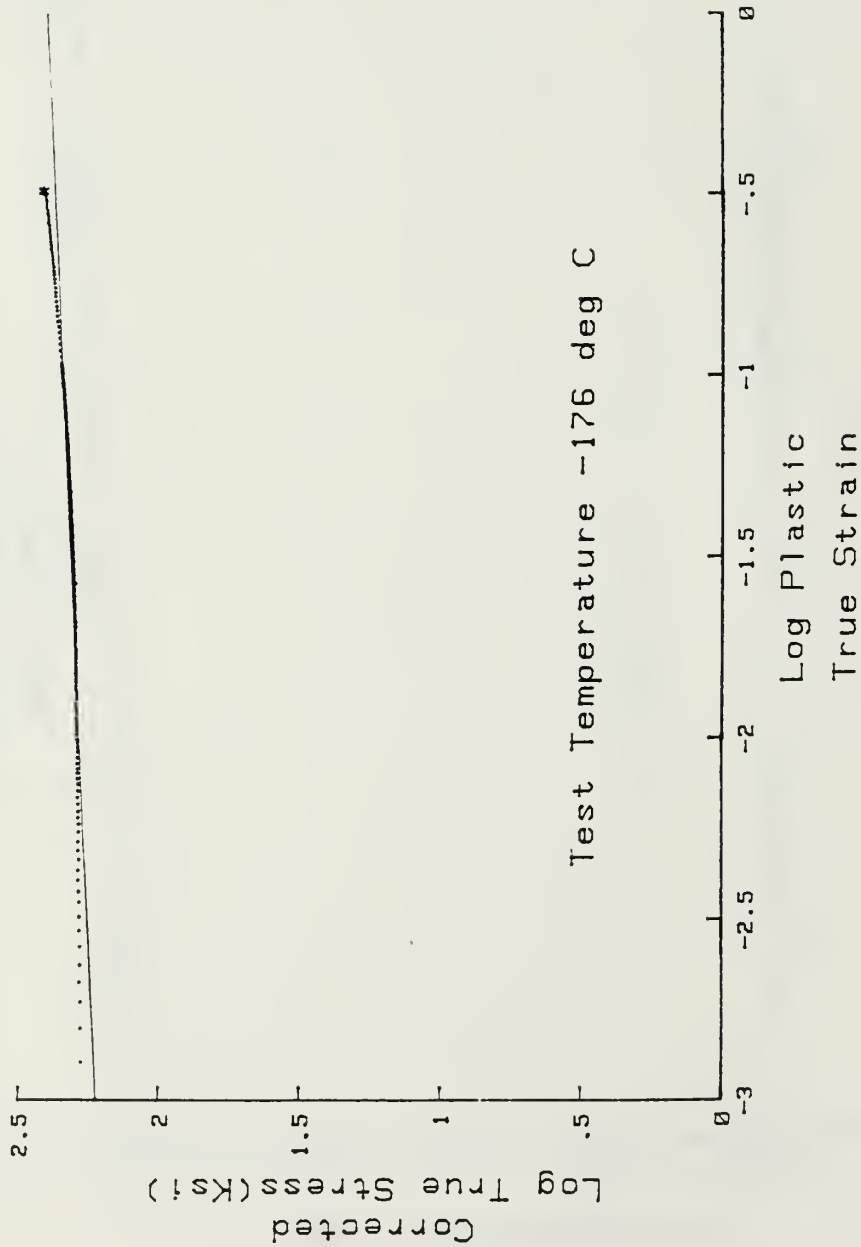


Figure 27. Log True Stress (Corrected for Necking) - Log True Plastic Strain Curve for Hourglass Specimen No. 7, Tested at -176 C, \* Indicates Fracture Point



# HSLA-100 STEEL YIELD STRENGTH VS. TEMPERATURE

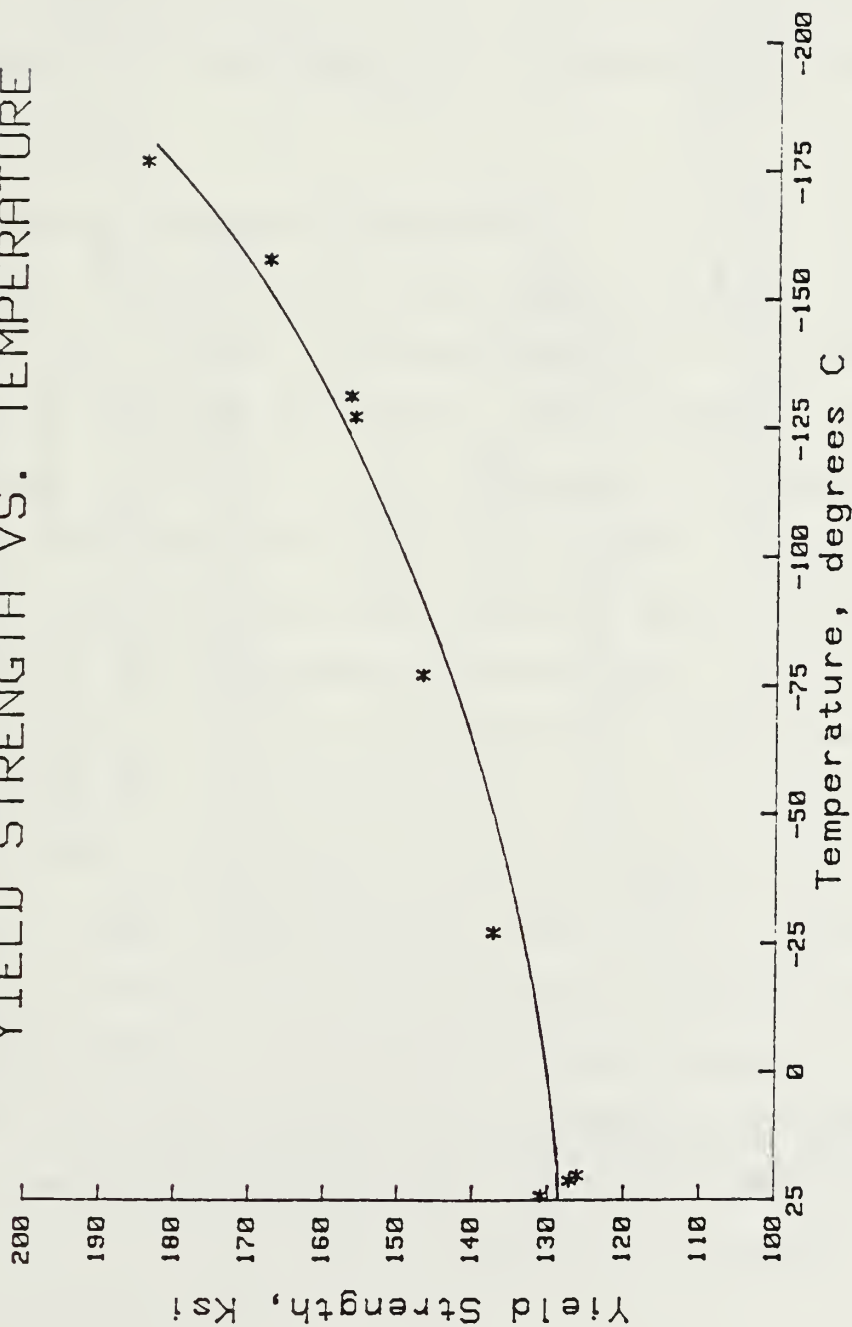


Figure 28. Yield Strength vs. Temperature for the Hourglass Specimens

# HSLA - 100 STEEL % R/A VS. TEMPERATURE

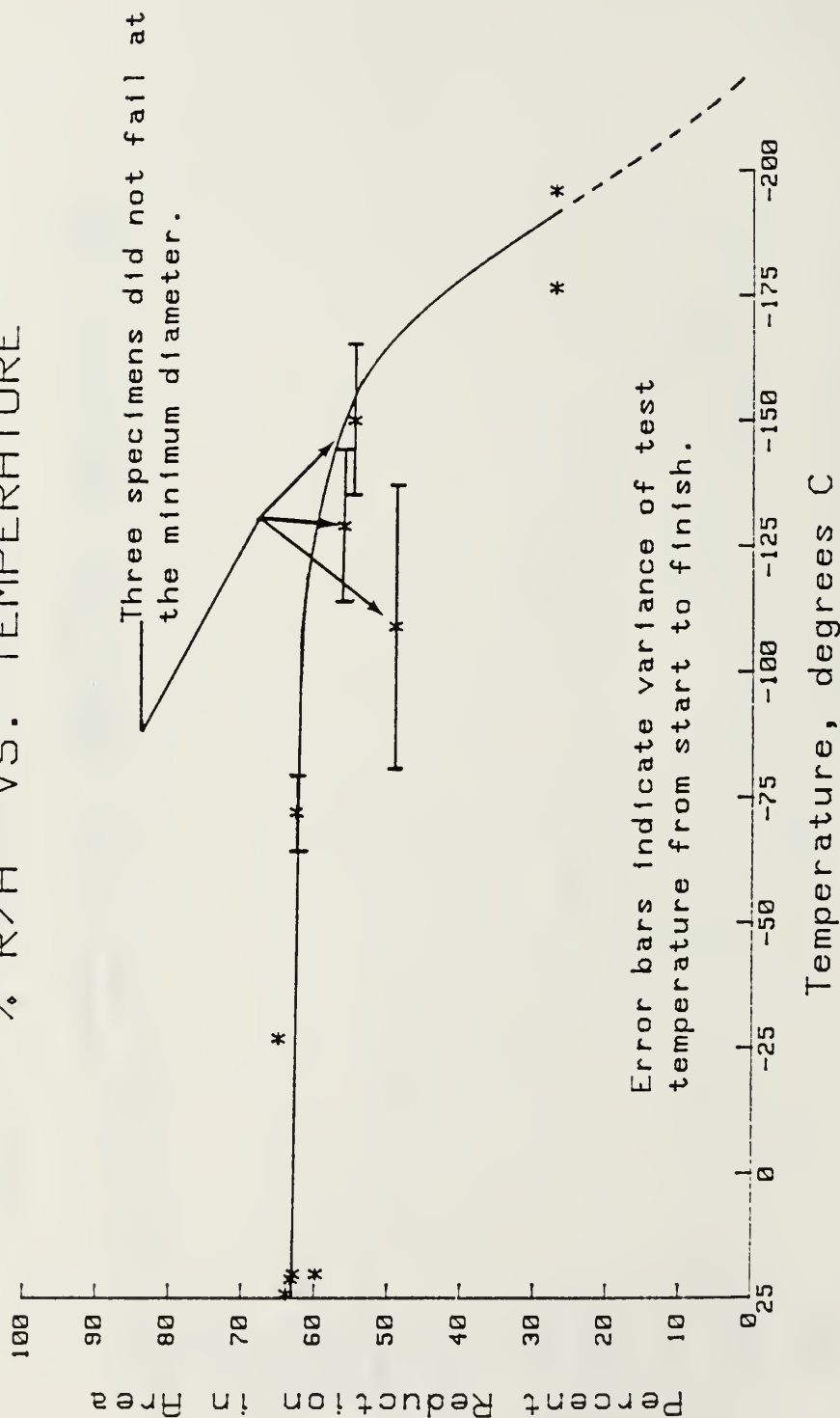


Figure 29. % R/A vs. Temperature for the Hourglass Specimens

diametral extensometer remained in the necked region, following the deformation process throughout these three tensile tests. The fracture surfaces of specimens 6, 11 and 12, revealed a mixture of ductile and cleavage behavior. All three experienced axial cracking (parallel to the specimen axis). A discussion on the cracks, known as delaminations or separations, is contained in the section titled microscopy observations.

#### E. CONSTITUTIVE EQUATION TESTING

In this research the Holloman power function, described earlier, was tested for applicability as a constitutive equation to describe the stress - strain behavior of HSLA - 100 steel. Table III is a tabulation of power law fit constants determined for each test specimen. The constants were determined using a least squares approximation (as discussed in the experimental section [Ref. 30]) to the log true corrected stress - log true plastic strain behavior of the material.

A value of  $R$  equal to one is a perfect fit of the straight line; a correlation above .98 is considered a good fit. The calculations necessary to produce the results listed in Table III are performed by the program in Appendix F. The wide variation in the strength coefficient, and strain hardening exponent and the low values of the

correlation coefficient indicate that the Holloman power law is not very applicable to HSLA - 100 Steel.

TABLE III

CONSTANTS FOR POWER LAW FIT (HOURLGLASS SPECIMEN)

No.	Temperature (deg C)	Strain Rate -4 x10/sec	Strain Hardening Exponent n	Strength Coefficient K (ksi)	Correlation Coefficient R
4	20	9.30	0.0464	183.0	.981
5	24	9.26	0.0779	204.2	.972
6	-109	9.30	0.0721	225.7	.962
7	-176	9.26	0.0585	255.9	.911
8	-196	9.35	a	a	a
9	-72	9.26	0.0660	213.3	.980
10	-27	9.26	0.0610	204.9	.989
11	-150	9.35	0.0600	237.0	.971
12	-129	9.30	0.0783	240.3	.975

UNIFORM GAGE-LENGTH SPECIMEN

1	20	4.34	0.0465	173.6	.989
2	22	9.28	0.0402	164.7	.969

a - no data collected.

The apparent good fit illustrated in Figures 26 and 27 is lost when the corrected log true stress scale is expanded. An expanded corrected log true stress versus log plastic true strain plot is shown for specimens 9 and 10, whose correlation coefficients were high (above .980), in Figures 30 and 31. The data follows a flattened "S" shape instead of the straight line as predicted by the Holloman power law. This flattened "S" shape was observed in the corrected log true stress - log plastic true strain plots

# HSLA-100 HOURGLASS

SPECIMEN NO.9

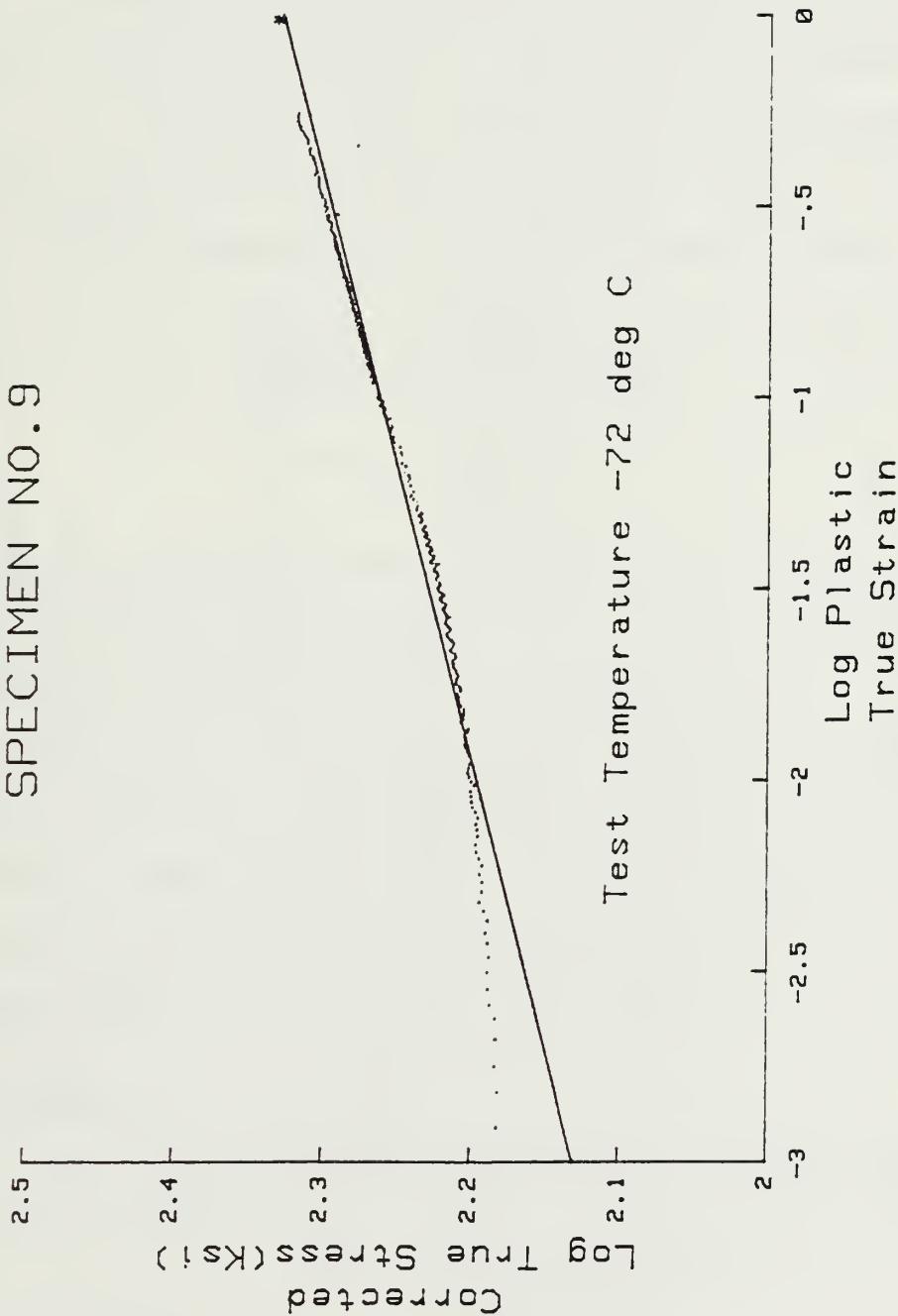


Figure 30. Log True Stress (Corrected for Necking) - Log True Plastic Strain Curve for Hourglass Specimen No. 9, Tested at -72 C, \* Indicates Fracture Point



# HSLA-100 HOURGLASS SPECIMEN NO. 10

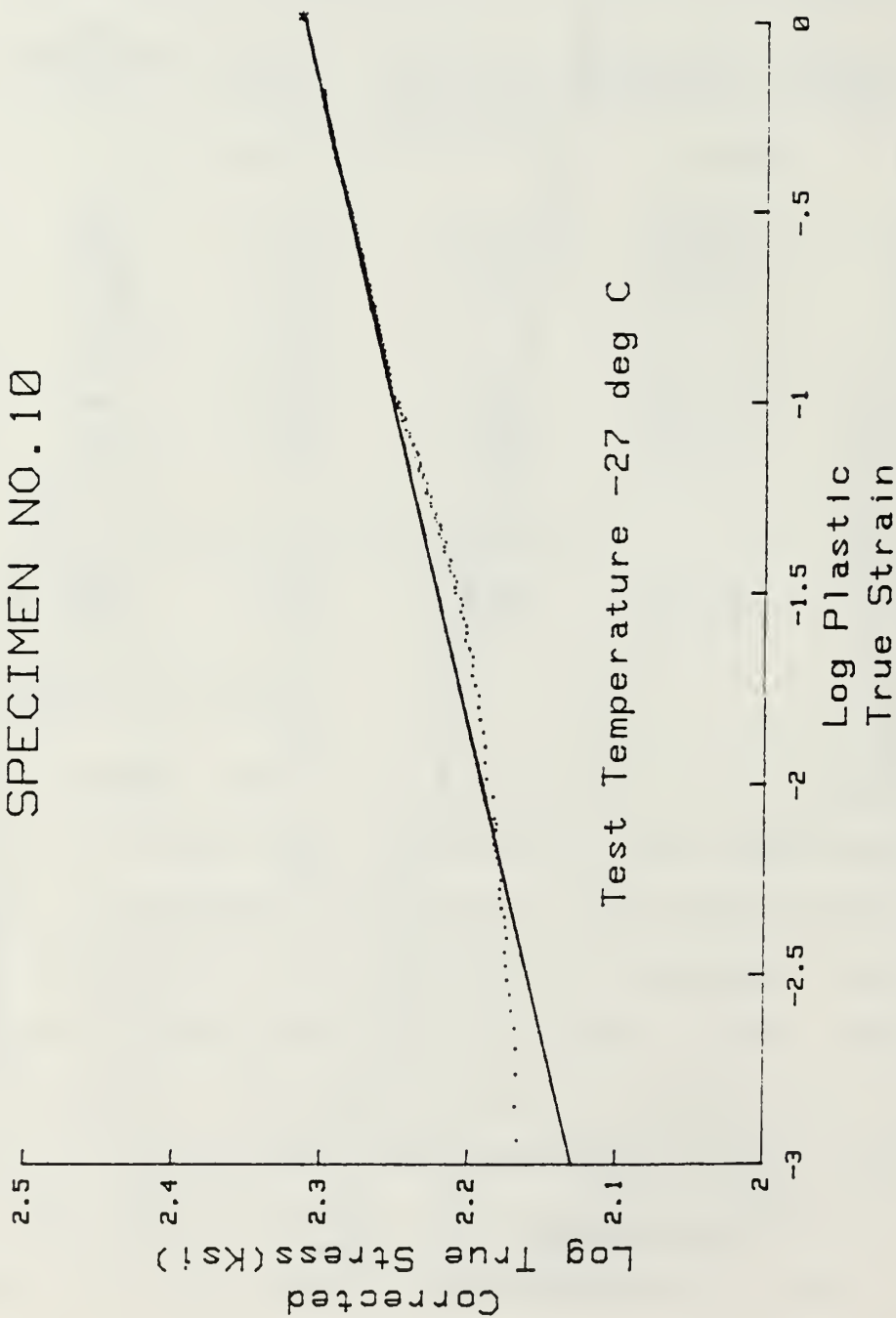


Figure 31. Log True Stress (Corrected for Necking) - Log True Plastic Strain Curve for Hourglass Specimen No. 10, Tested at -27 C, \* Indicates Fracture Point

for all the specimens tested. Closer scrutiny of Figures 26 and 27, for specimens 5 and 7, reveals a flattened " S " shaped curve even on the broad corrected log true stress scale.

Conway [Ref. 21:pp. 163-169] discusses an alternative stress - strain relation when the use of the power law is precluded. When the log true stress - log true strain curve results in a flattened " S " shape, see Figures 24 and 25, the power law is not applicable. The alternative stress - strain relation, purported to accurately describe the type of behavior reported herein, is the Voce relation [Ref. 18]. The Voce relation is expressed as follows:

$$S = S_{\infty} - (S_{\infty} - S_0) e^{-\epsilon/k}$$

Where  $S$  is the true stress,  $S_{\infty}$  the final constant stress attained at very large strains,  $S_0$  is the initial stress corresponding roughly with the 0.1% yield stress.  $\epsilon$  is the true strain,  $k$  is a constant and  $e$  represents the natural logarithm function. A development of the Voce relation is presented by Conway [Ref. 21:pp. 160-174]. Although the Voce relation will not be discussed further herein, a logical follow on to this work would be to test its applicability.

#### F. FRACTOGRAPHY

With the exception of the samples tested below -150 C, the fracture surfaces were characterized by delaminations,

which occurred as cracks running parallel to the rolling direction. The specimens tested between -100 C and -150 C did not fail at the minimum diameter. In these specimens the actual fracture surface occurred between .125 in. and .150 in. from the minimum diameter. Two of these failures occurred above the minimum diameter and one occurred below the minimum diameter.

Figure 32 is a photograph of the specimen tested at -109 C and is typical of the specimens which did not fail at the minimum diameter. In Figure 32 the delamination, running parallel to the specimen longitudinal axis is quite evident. The fracture surface of this specimen is characterized by a mixed ductile-brittle fracture mode, Figure 33. Near the delamination very fine microvoids, characteristic of ductile failure, are evident. While further from the delamination cleavage facets prevailed. These failure modes, ductile and brittle can be seen more clearly in Figures 34 (a) and 34 (b), respectively. The origin of the delaminations, which are planes of weakness parallel to the deformation direction, is still controversial. One possible explanation is that an aligned microstructure, due to the deformation, coupled with inclusions and/or grain boundary carbides provide the weak interfaces which allow the delamination to occur [Ref. 31]. However, other authors have reported that this is not the sole mechanism contributing to this behavior; but that crystallographic texture is also important [Refs. 32,33].

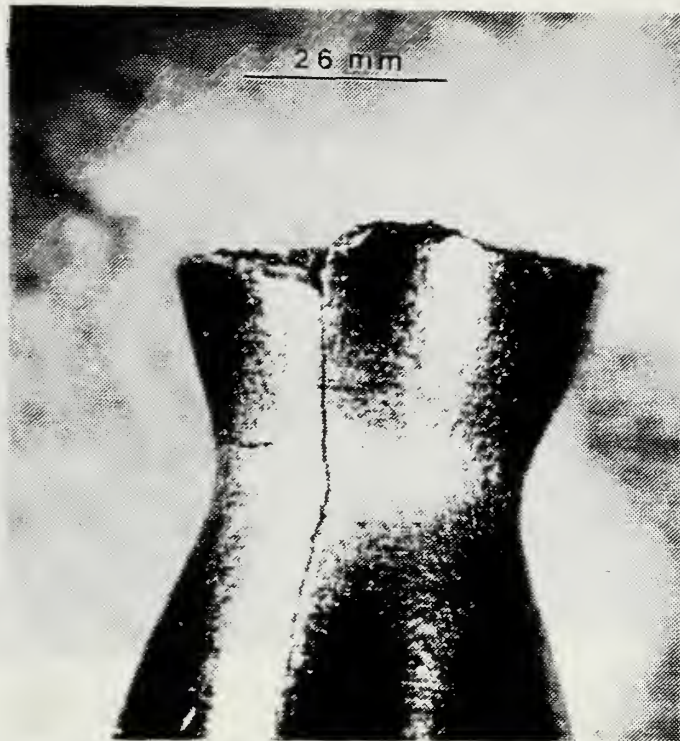


Figure 32. Hourglass Specimen No. 6

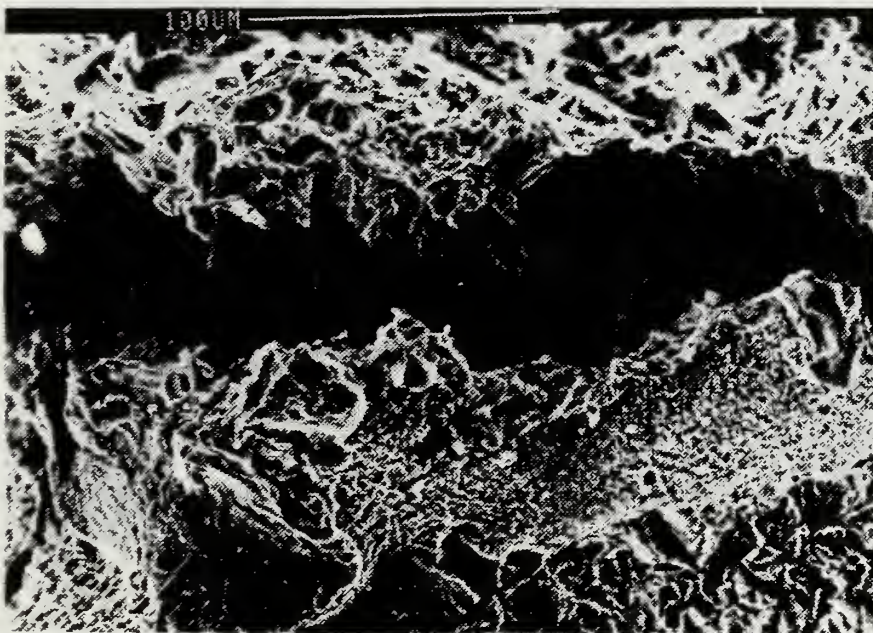
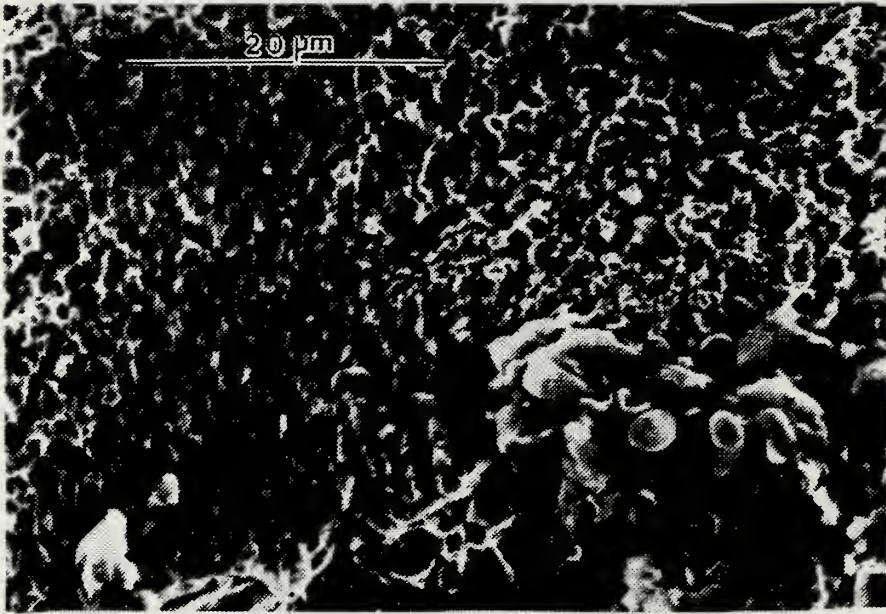
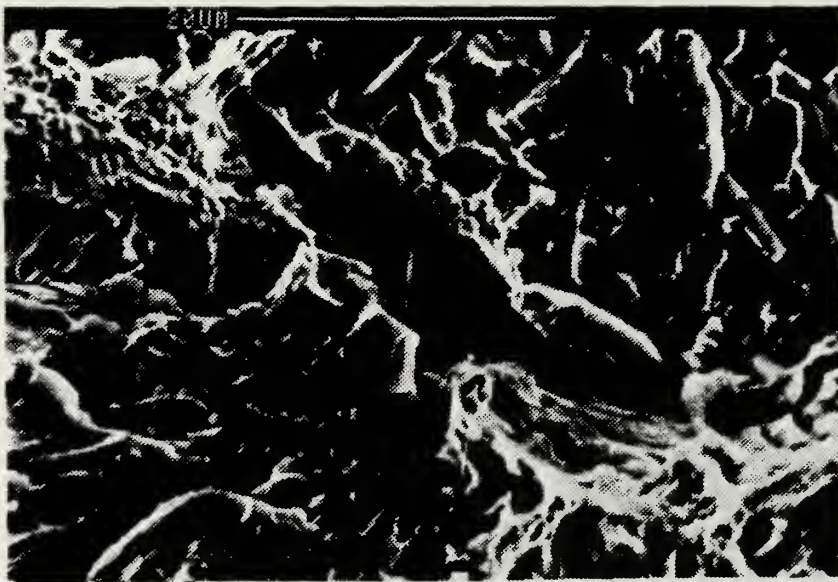


Figure 33. Fracture Surface of Hourglass Specimen No. 6





(a)



(b)

Figure 34. Fracture Surface of Specimen No. 6 (a) Adjacent to the Delamination (b) Adjacent to the area in (a), away from the Delamination



## V. CONCLUSIONS AND RECOMMENDATIONS

### A. CONCLUSIONS

The HSLA - 100 steel tested in this research has excellent ductility above - 150 C. Rapidly increasing yield strength is observed as temperature decreases.

The Hollomon power function should not be used as the constitutive equation for HSLA - 100 steel as it does not satisfactorily describe the stress - strain response of this steel.

### B. RECOMMENDATIONS

The effect of temperature on the tensile properties of properly heat treated HSLA - 100 steel plate should be determined.

The Voce relation should be tested for applicability as a constitutive equation to describe the stress - strain response of HSLA - 100 steel.

Tensile testing at higher strain rates should be conducted to determine the effect of strain rate, in addition to the effect of temperature, on the toughness behavior of HSLA - 100 steel.

## APPENDIX A

### INTERIM SPECIFICATION FOR TRIAL COMMERCIAL PRODUCTION OF HSLA-100 STEEL PLATES

#### Melting, Refining and Casting

The heat shall be fully killed and produced to fine grain practice. It shall be made with a low sulfur practice, vacuum degassed and argon injected with CaSi or Mg for sulfide shape control. The heat shall be ingot cast with bottom-pour molds to ensure good surface.

#### Chemical Composition

The chemical composition shall be as shown in Table I.

Table I - Chemical Composition (Heat and Product  
Analysis)

ELEMENT	TARGET for First Heat	Max. % by Weight Unless a Range is Indicated
Carbon	0.04	0.06
Manganese	0.90	0.75 - 1.05
Phosphorus	ALAP*	0.015
Sulfur	ALAP	0.006
Silicon	0.25	0.40
Nickel	3.50	3.35 - 3.65
Chromium	0.60	0.45 - 0.75
Molybdenum	0.60	0.55 - 0.65
Copper	1.60	1.45 - 1.75
Columbium	0.025	0.02 - 0.06
Aluminum	0.030	0.020 - 0.040
Nitrogen	0.010	0.015

\* As low as possible

## Hot Rolling

Plates 1/4, 3/4, 1-1/4, and 2 in. thick shall be rolled. Extra care shall be taken to minimize rolled-in scale that could later interfere with achieving an adequate cooling rate during quenching from the solution treating temperature. The plates shall be roller leveled while still warm after rolling.

## Heat Treatment

All of the plates shall be solution heat treated for one hour at 1650 F ( 934 C ) and platen quenched with high pressure water jets from above and beneath the plate. The quench water shall not exceed 100 F to ensure an efficient quench.

The plates shall be given an age hardening treatment using temperatures and times determined for each plate by preliminary tensile testing of samples from coupons aged at various conditions. Aging conditions for the plates shall be chosen so as to give the tensile properties listed in Table II.

## Mechanical Properties

The heat treated material shall meet the tensile property requirements specified in Table II and the impact property requirements specified in Table III.

Table II - Tensile Properties

Ultimate Tensile Strength, psi	To be recorded for Information Only	
Yield Strength, 0.2% Offset, psi	<0.75 in. 100,000 to 120,000	>0.75 in. 100,000 to 115,000
Min. Elongation in 2 in., %	17	18
Min. Reduction Area, Round Specimen, %	--	45

The tensile properties shall be determined as the average value of duplicate specimens from each plate tested in accordance with ASTM method of testing E8. Full thickness flat specimens shall be tested for the 1/4 - in. thick plate and standard round specimens 0.505 in. in diameter shall be tested for the plates 3/4 in. thick and thicker. All specimens shall be taken transverse to the primary rolling direction.

Table III - Impact Properties

Test	Plate Thickness, in.	Specimen Size	Test Temp., F	CVN Energy, ** ft-lb
Charpy V-Notch Transverse	0.25	5mm x 10mm	0 + 3	28
			-120 + 3	15
	0.75, 1.25, 2.00	10mm x 10mm	0 + 3	55
			-120 + 3	30

\*\* Avg. of three tests, minimum.

The Charpy impact properties shall be determined in accordance with ASTM method E23. Three tests transverse to the final rolling direction of the plate shall be conducted. No single value shall fall below the minimum average specified in Table III by more than 5 ft-lb for standard specimens and 2-1/2 ft-lb for half size specimens.



## APPENDIX B

### CHECKLIST AND EXAMPLE SETTINGS

The purpose of this appendix is to provide a detailed checklist for conducting tensile tests on a Materials Testing System (MTS) 810 series system. The form of this appendix is that of an operators checklist followed by an operational sequence for conduction the constant strain rate tensile test. It provides a sequence of operations and references to information in the system technical manuals. Nominal testing parameters are as follows:

1. Strain rate :  $9.30 \times 10^{-4}$  /sec.
  2. Total diametral displacement range = 0.072 in.
  3. A tensile test will be set up herein using a dual slope, hold at breakpoint, ramp and invert function generator set up to allow full extensometer travel.
  4. The initial diameter of the specimen will be 0.25 in. and the initial specimen gage length will be 1.00 in. as in Figure 8 for a hourglass shaped specimen.
  5. Note: Safe operation of MTS equipment is contingent upon knowledge contained in the introductory section of the system operating manual.
- 
-

CHECK  
PROCEDURE

RECORD  
ADJUSTMENT

MANUAL  
REFERENCE

..... CONSOLE TURN ON .....

- \_1. Turn CONSOLE POWER on 413.05 OP,  
page 2

..... PRELIMINARY ADJUSTMENT .....

- \_2. If the load cell, Extensometer 440.21 OP,  
clip-on gage, or LVDT is changed, page 6  
ensure that the proper range card  
is installed in the appropriate 440.22 OP,  
transducer conditioner. NOTE: CRY- page 6  
ogenic diametral extensometer  
model No. 632.19B-21

..... PROGRAMMING .....

- \_3. Select desired controlled X LOAD 440.31 OP,  
variable. Control panel      STRAIN page 2  
interlock must be open      STROKE  
(RESET lit).

- \_4. Select desired LOAD +% FS RANGE 440.21 OP,  
operating range. Full Scale = + 20 KIP page 3

<u>    </u>	100	1
<u>X</u>	50	2
<u>    </u>	25	3
<u>    </u>	10	4

STRAIN  
+ FS=.040 IN. RANGE 440.21 OP,  
page 3

<u>    </u>	100	1
<u>X</u>	50	2
<u>    </u>	25	3
<u>    </u>	10	4

STROKE + FS 440.22 OP,  
FULL SCALE = + 3 in. page 3

<u>    </u>	100	1
<u>    </u>	50	2
<u>    </u>	25	3

CHECK  
PROCEDURE

RECORD  
ADJUSTMENT

MANUAL  
REFERENCE

	<u>X</u> 10 4	
<u>5.</u> Adjust Digital Function Generator	CONTROL MODE	410.31 OP,
	<u>      </u> REMOTE	
	<u>X</u> LOCAL	
	<u>      </u> SINGLE CYCLE	
	OUTPUT	
	<u>X</u> RAMP	
	<u>      </u> SINE	
	<u>      </u> HAVERSINE	
	<u>      </u> HAVERSQUARE	
	<u>X</u> INVERT	
	BREAKPOINT	
	REMOTE	
	<u>X</u> NORMAL	
	<u>      </u> REVERSE	
	LOCAL	
	<u>X</u> NORMAL	
	<u>      </u> REVERSE	
	<u>90</u>	
	PERCENT	
	<u>X</u> DUAL SLOPE	
	<u>X</u> HOLD AT BRKPT	
	<u>      </u> RAMP THRU ZERO	
	<u>      </u> MANUAL BRKPT (OVERRIDE)	
	<u>360</u>	
	RATE 1	
	<u>1000</u>	
	RATE 2	
<u>6.</u> Adjust SPAN 1 for desired Digital Function Generator signal amplitude.	<u>100</u> SPAN 1	440.13 OP, pages 3-7
<u>7.</u> Adjust Digital Display	INPUT SELECT	430.41 OP,

indicator.

page 2

X 1 (LOAD)  
X 2 (STRAIN)  
X 3 (STROKE)  
   4 ( INPUT options 4-6 are  
          available ).

..... FAILSAFE ADJUSTMENTS .....

\_8. Adjust Limit Detectors, XDCR 1 (LOAD) 440.41 OP,  
if applicable. page 4

100  
UPPER

NOTE:

This step may be  
performed after test  
has started. See  
440.41 OP, page 5

  X (+)  
   (-)

10  
LOWER

   (+)  
  X (-)

  X INTERLOCK  
   INDICATE

XDCR 2 (STRAIN) 440.41 OP,  
page 4

100  
UPPER

  X (+)  
   (-)

100  
LOWER

   (+)  
  X (-)

  X INTERLOCK  
   INDICATE

CHECK  
PROCEDURE

RECORD  
ADJUSTMENT

MANUAL  
REFERENCE

XDCR 3 (STROKE)  
100  
UPPER

440.41 OP,  
page 4

  X   (+)  
      (-)

 100   
LOWER

      (+)  
  X   (-)

  X   INTERLOCK  
      INDICATE

..... PRELIMINARY ADJUSTMENTS AND HYDRAULIC TURN ON .....

\_9. Monitor DC ERROR on the Controller meter. 440.13 OP,  
page 8

\_10. Null the meter using the SET POINT control. 440.13 OP,  
page 3

\_11. Push RESET on the Control Panel if it is lit. 413.05 OP,  
page 2

NOTE: If at any time  
RESET will not extinguish,  
look for an abnormal  
condition as described on  
the last page of this checklist  
under IN CASE OF SYSTEM SHUTDOWN.

\_12. Set AUTO RESET switch to OUT. 440.14/.14A OP,  
page 2

\_13. Push HYDRAULIC PRESSURE on the Control Panel (LOW pressure condition). 413.05 OP,  
page 6

If at any time an emergency occurs, push EMERGENCY STOP

..... INSTALLING THE SPECIMEN .....



CHECK  
PROCEDURE

RECORD  
ADJUSTMENT

MANUAL  
REFERENCE

- \_14. Lower Hydraulic Actuator SET POINT CONTROL full CCW  
to bottom stop; then turn  
off hydraulic pressure.
- \_15. Install specimen in the upper grip.  
Tighten collar with spanner wrench.  
Plug thermocouple(s) into receptacles.
- \_16. Push reset on Control Panel  
and select low pressure. By  
adjusting the SET POINT control  
CCW slowly raise the actuator up to  
the specimen. Thread the locking collar  
into the lower grip, as the actuator  
moves upward, using the spanner wrench.
- \_17. Check that LOAD is zeroed. Adjust 440.21 OP,  
if necessary. page 6

..... MOUNTING THE EXTENSOMETER .....

- \_18. The extensometer is clamped to the See Technical  
specimen with a spring-loaded arm on Manual-  
one side and an adjustable station- TRANSDUCERS  
ary arm on the other. The adjustable  
arm contact can be changed to the  
desired gage length by loosening the  
contact hold-down screws, moving the  
contact to the desired gage length,  
and the retightening the hold-down  
screws. To obtain 0.072 in. of diametral  
travel preset extensometer to near -9.0  
volts then adjust to -9.000 volts using the  
zero adjust.

..... ZERO ADJUSTMENT .....

- \_19. Once the extensometer is attached 440.21 OP,  
to the specimen, its electrical page 4  
output may be adjusted to desired  
voltage using the zero adjust on  
the strain transducer conditioner.

..... RUNNING A TENSILE TEST .....

20. Turn console power on
21. Select desired test temperature on the temperature controller. Attatch thermocouple to desired locale for controlling the temperature.
22. With the enviromental chamber door closed turn the temperature controller to cool. Open the liquid output valve on the cooling medium container.
23. Bring specimen to the desired test temperature. Ensure that temperature has equilibrated on the specimen by monitoring thermocouple temperatures for the two thermocouples attatched to the specimen.
24. Press return to zero on the function generator.
25. Press MTS 440.37 process controller clear D/A button.
26. Select strain control.
27. Zero contoller meter using set point potentiometer.
28. Press interlock resets on MTS 445 and then MTS 413.
29. Set rate 1 on the function generator to 10 sec. and rate 2 to 1 sec.
30. Turn on the Tektronics oscilloscope.
31. Press start on the function generator. When, in 10 sec., the oscilloscope sweep reaches -9 volts press function generator hold button.
32. Set fuction generator rate to 360 sec. and rate 2 to 1000 sec.
33. Zero the controller meter using the set point potentiometer.
34. Clear interlock resets on MTS 445 then MTS 413.
35. Turn on hydraulics in low then switch to high pressure.
36. Turn on the 9826 Hewlitt Packard computer, DVM, printer and plotter.
37. Boot up data collection program "JHCOLLECT". Press run and input the requested values.
38. Set the MTS 445 controller recorder dials to Y1 = load, Y2 = strain and X = stroke, this sends these values to channels 1-3 on the DVM.
39. Set the MTS 445 controller osicilloscope dials to Y1 = load, Y2 = off, and X = strain. Then run leads to the chart recorder. The abscissa is strain and the ordinate is load. Set chart recorder at 1 volt/in.
40. To start the test, press the computer soft key labeled start and release the function generator hold button.
41. If full extensometer travel is reached prior to the specimen fracturing, stop hydraulics and pause the data collection program.
42. Set function generator rate 2 to one sec. and press return to zero.
43. Select stroke control on the MTS 445 controller and zero the meter using the set point potentiometer.
44. Change the controller oscilloscope X dial to stroke.

45. Press interlock resets on the MTS 445 and then the MTS 413.
46. Turn on hydraulics in low pressure then switch to high.
47. Press continue on the data collection program.
48. While observing the chart recorder plot SLOWLY load the specimen to the point of fracture. This is done by manually adjusting the set point control in the clockwise direction.
49. When the specimen fractures press stop hydraulics on the MTS 413 master control panel.
50. Press test stop on the data collection program.
51. Secure the flow of the cooling medium to the environmental chamber.
52. Turn off console power. When the environmental chamber is at room temperature the specimen can be removed.

## APPENDIX C

### BASIC COMPUTER PROGRAM FOR DATA COLLECTION

```

110 ! *****
120 ! PROGRAM STORED AS 'JHCOLLECT'
130 ! TENSILE CHARACTERISTICS VS TEMP HSLA 100
140 ! THE PURPOSE OF THE PROGRAM IS TO COLLECT
150 ! THE FOLLOWING FOUR PARAMETERS DURING
160 ! CONSTANT STRAIN RATE TENSILE TESTS AT
170 ! VARIOUS TEMPERATURES. THE DATA IS STORED
180 ! IN ARRAYS FOR SUBSEQUENT MANIPULATION AND
190 ! PLOTTING. THE PROGRAM ALSO ALLOWS PLOT-
200 ! OF THE LOAD VS. DIAMETRAL DISPLACEMENT
210 ! DATA OBTAINED HEREIN.
220 ! PARAMETERS:
230 !     Lcd = LOAD
240 !     Dia = DIAMETRAL DISPLACEMENT
250 !     Stk = MACHINE ACTUATOR STROKE
260 !     Itime = TIME OF TEST RUN
270 ! *****
280 !
290 ! DIMENSION THE ARRAYS FOR STORING DATA
300 DIM Lcd(500),Stk(500),Dia(500),Itime(500)
310 PRINTER IS !CRT
320 Select : ! CREAT DATA FILES
330 PRINT "Select program using softkeys."
340 OFF KEY
350 ON KEY 0 LABEL "CREATE BDATA" GOTO D_form
360 ON KEY 4 LABEL "RENAME DATA FILE" GOTO R_nam
370 ON KEY 5 LABEL "E STOP" GOTO S_10
380 ON KEY 9 LABEL "RUN TEST" GOTO T_test
390 Start_idle: GOTO Start_idle
400 T_test: !
410 End_test=0 !0 for test in prog 1 for test stopped
420 Dvm=709 ! ADDRESS OF HP3497A
430 CLEAR Dvm !INITIALIZES HP3497A
440 Set up: ! INITIALIZE MTS TEST SET UP
450 PRINTER IS !
460 PRINT USING "@,@"
470 OFF KEY
480 PRINT "ENTER LOAD TRANSDUCER RANGE 1-4"
490 PRINT "OR PRESS KEY 0 FOR CANNED DATA"
500 Icond=1 ! TRANSDUCER CONDITIONER #1
510 GOSUB Range_set
520 PRINT "ENTER STRAIN TRANSDUCER RANGE 1-4"
530 Icond=2 ! TRANSDUCER CONDITIONER #2
540 GOSUB Range_set
550 PRINT "CHOOSE EXTENSOMETER TYPE",Extens$, "THEN CONTINUE"
560 Strain_go: OFF KEY
570 ON KEY 0 LABEL "DIAMETRAL" GOTO Diam
580 ON KEY 4 LABEL "LONGITUDINAL" GOTO Long
590 ON KEY 9 LABEL "CONTINUE" GOTO Axe
600 Strain_wait: GOTO Strain_wait
610 Axe: !
620 PRINT "EXTENSOMETER TYPE IS ",Extens$
630 BEEP 300,.5
640 PRINT "ENSURE PROPER DISPLACEMENT IS ENTERED WHEN REQUESTED"
650 PRINT "ENTER STROKE TRANSDUCER RANGE 1-4"
660 Icond=3 ! TRANSDUCER CONDITIONER #3
670 GOSUB Range_set
680 OFF KEY
690 Initstr=0 !THIS IS THE STARTING POINT FOR ACTUATOR STROKE
700 Instr=0 !THIS IS THE STARTING POINT FOR THE EXTENSOMETER

```

```

610 BEEP 500..3
620 PRINTER IS 1
630 PRINT USING "@.@"
640 PRINT "TURN ON THE DVM!!!!!!!!!!!!!!"
650 PRINT
660 PRINT "CHANGE THE DISC?????????"
670 PRINT "ENSURE MTS HYDRAULICS IN HIGH PRESSURE AT THIS POINT"
680 PRINT "PRESS 'CONTINUE' TO RESUME "
690 PAUSE
700 OUTPUT Dvm;"VR5 AF1 AL3" !SETS CHANNELS 1-3 TO AUTO RANGE
710 OUTPUT Dvm;"AI3 VT1" !READS PRESENT STROKE
720 ENTER Dvm:St
730 OUTPUT Dvm;"AI2 VT1" !READS PRESENT STRAIN
740 ENTER Dvm:Str
750 PRINT " INITIAL STROKE PER DVM=";St
760 PRINT " INITIAL STRAIN PER DVM=";Str
770 Bstroke=Initstr-Istroke*St!BSTROKE SET BY INITIAL CONDITIONS
780 INPUT "Specify maximum strain transducer output, V",Max_str
790 INPUT "Specify displacement at this voltage,in inches",Max_disp
800 ! THE FOLLOWING ACCOUNTS FOR TRANSDUCER RANGE SETTINGS
810 Istrain=Istrain*(Max_disp/Max_str)
820 Bstrain=Instr-Istrain*Str!BSTRAIN SET BY INITIAL CONDITIONS
830 GOTO G_1
840 Long: !
850 Extenso$="Longitudinal"
860 GOTO Strain_go
870 Diam:!
880 Extenso$="Diametral"
890 GOTO Strain_go
900 G_1:INPUT "Gauge length, inches?",Gage
910 PRINT "gauge length=";Gage;" inches"
920 INPUT "Initial diameter, inches?",D_0
930 A_0=(PI/4)*(D_0^2)
940 GOTO Begin
950 Range_set: ! SUBROUTINE TO INPUT RANGES AND TO CONVERT
960 ! VOLTAGES TO ENGINEERING UNITS
970 OFF KEY
980 ON KEY 0 LABEL "TEST DATA" GOTO Test_dat
990 ON KEY 1 LABEL "RANGE 1 = 100%" GOTO R_1
1000 ON KEY 2 LABEL "RANGE 2 = 50% " GOTO R_2
1010 ON KEY 3 LABEL "RANGE 3 = 20% " GOTO R_3
1020 ON KEY 4 LABEL "RANGE 4 = 10% " GOTO R_4
1030 R_s: GOTO R_s
1040 R_1: PRINT "Range 1 selected."
1050 IF Icond=1 THEN Iload=2.0
1060 IF Icond=2 THEN Istrain=1.0
1070 IF Icond=3 THEN Istroke=.50
1080 RETURN
1090 R_2:PRINT "Range 2 selected."
1100 IF Icond=1 THEN Iload=1.0
1110 IF Icond=2 THEN Istrain=.5
1120 IF Icond=3 THEN Istroke=.250
1130 RETURN
1140 R_3:PRINT "Range 3 selected."
1150 IF Icond=1 THEN Iload=.4
1160 IF Icond=2 THEN Istrain=.2
1170 IF Icond=3 THEN Istroke=.100
1180 RETURN
1190 R_4:PRINT "Range 4 selected."
1200 IF Icond=1 THEN Iload=.2

```



```

1210 IF Icond=2 THEN Istrain=.10
1220 IF Icond=3 THEN Istroke=.050
1230 RETURN
1240 Begin: !still setting up
1250 I=1
1260 INPUT "HOW MANY READINGS PER TEST 500 MAX?".Rdg
1270 PRINT Rdg:" readings selected."
1280 PRINT "THE INTERNAL TRIGGERING OF THE DVM"
1290 PRINT "ALLOWS APPROXIMATELY 2 READINGS OF THE"
1300 PRINT "FOUR VARIABLES PER SECOND WITH NO ADDITIONAL DELAY"
1310 INPUT "ADDITIONAL SECONDS BETWEEN READINGS 1 AND 50".Delay
1320 INPUT "ADDITIONAL SECONDS BETWEEN READINGS 51 AND 200".Delay1
1330 INPUT "ADDITIONAL SECONDS BETWEEN READINGS 201 AND 400".Delay2
1340 INPUT "ADDITIONAL SECONDS BETWEEN READINGS 401 AND 500".Delay3
1350 Cal_x: !
1360 OFF KEY
1370 PRINT
1380 PRINT "TEST SET UP AS FOLLOWS:"
1390 PRINT "FOR ICOND=1, 1 VOLT = ";Iload;"Kip"
1400 PRINT "FOR ICOND=2, 1 VOLT = ";Istrain;"IN"
1410 PRINT "FOR ICOND=3, 1 VOLT = ";Istroke;"IN"
1420 PRINT
1430 PRINT "TYPE EXTENSOMETER IS ";Extensom$
1440 PRINT "NUMBER OF READINGS =";Rdg
1450 PRINT "DELAY BETWEEN READINGS 0-50=";Delay;"SECONDS"
1460 PRINT "DELAY BETWEEN READINGS 51-200=";Delay1;"SECONDS"
1470 PRINT "DELAY BETWEEN READINGS 201-400=";Delay2;"SECONDS"
1480 PRINT "DELAY BETWEEN READINGS 401-500=";Delay3;"SECONDS"
1490 PRINT "Press softkey to start or to change set up."
1500 BEEP 1000,.1
1510 ON KEY 0 LABEL "Start" GOTO Starter
1520 ON KEY 2 LABEL "Fix G.L." GOTO G_1
1530 ON KEY 4 LABEL "Change" GOTO Set_up
1540 Begin_idle: GOTO Begin_idle
1550 Starter: !
1560 PRINT "Data Acquiring"
1570 OFF KEY
1580 Starter2: ! This interrupts data acq & restarts when "CONTINUE" is press
1590 ON KEY 1 LABEL "pause" GOTO Test_pause
1600 ON KEY 4 LABEL "STOP" GOTO Test_complete
1610 IF I<=50 THEN WAIT Delay
1620 IF I>50 AND I<200 THEN WAIT Delay1
1630 IF I>200 AND I<400 THEN WAIT Delay2
1640 IF I>400 THEN WAIT Delay3
1650 Data_acq: ! DATA ACQUISITION ROUTINE
1660 IF I=1 THEN T_0=TIMEDATE
1670 OUTPUT Dvm:"VR5 AFO AL3" !SETS CHANNELS 1-3 TO AUTO RANGE
1680 OUTPUT Dvm:"AI1 VT1" !READS LOAD
1690 ENTER Dvm:Lod(I) !PUTS VOLTS INTO VARIABLE
1700 OUTPUT Dvm:"AI2 VT1" !READS STRAIN
1710 ENTER Dvm:Dia(I) !PUTS VOLTS INTO VARIABLE
1720 OUTPUT Dvm:"AI3 VT1" !READS STROKE
1730 ENTER Dvm:Stk(I) !PUTS VOLTS INTO VARIABLE
1740 Itime(I)=TIMEDATE-T_0
1750 I=I+1
1760 Lrdg=I ! LAST READING COUNTER FOR STOPPING TEST
1770 IF I>Rdg OR I>499 THEN Stopper
1780 GOTO Starter2
1790 Stopper: !
1800 PRINT "ACQUISITION COMPLETE"

```

```

1810 Count_out=1 ! COUNTING AND SORTING VARIABLE
1820 Conv_ss: !
1830 !CONVERT VOLTAGE DATA TO ENG UNITS LOAD,TEMP.STROKE,DISPL
1840 Lrdg=Lrdg-1
1850 FOR H=1 TO Lrdg
1860   Lod(H)=Lod(H)*Iload
1870   Stk(H)=Stk(H)*Istroke+Bstroke
1880   Dia(H)=Dia(H)*Istrain+Bstrain
1890 NEXT H
1900 !STORE DATA AS CONVERTED TO BDAT FILES
1910 OFF KEY
1920 Dat_out: !
1930 PRINTER IS 1
1940 PRINT USING "@,#"
1950 PRINT "Data is being stored. Sorry for the delay....."
1960 PRINT "Assigning to Load. etc."
1970 ASSIGN @Path1 TO "Lod"
1980 ASSIGN @Path2 TO "Dia"
1990 ASSIGN @Path3 TO "Stk"
2000 ASSIGN @Path4 TO "Itime"
2010 FOR I=1 TO Lrdg
2020   OUTPUT @Path1;Lod(I)
2030   OUTPUT @Path2;Dia(I)
2040   OUTPUT @Path3;Stk(I)
2050   OUTPUT @Path4;Itime(I)
2060 NEXT I
2070 FOR I=1 TO Lrdg
2080 ASSIGN @Path1 TO *
2090 ASSIGN @Path2 TO *
2100 ASSIGN @Path3 TO *
2110 ASSIGN @Path4 TO *
2120 NEXT I
2130 !OUTPUT THE DATA
2140 PRINT USING "@,#"
2150 PRINT "SELECT HARD OR SOFT COPY"
2160 PRINT "LOAD/DISP"
2170 OFF KEY
2180 ON KEY 0 LABEL "HARD COPY" GOTO Har
2190 ON KEY 4 LABEL "NO HARD COPY" GOTO Sof
2200 Stop_idle: GOTO Stop_idle
2210 Har: PRINTER IS 706
2220 Sof: !
2230 OFF KEY
2240 PRINT "      I          LOAD          DISPL          STROKE          TIME"
2250 PRINT "      (KIP)        (IN)        (IN)        (SEC)"
2260 FOR I=1 TO Lrdg
2270   PRINT USING Fmt1;I,Lod(I),Dia(I),Stk(I),Itime(I)
2280 NEXT I
2290 Fmt1: IMAGE DDD.5X.4(1X.SD.DDE)
2300 OFF KEY
2310 Plotz: !
2320 DEG
2330 OFF KEY
2340 PRINT "Choose whether or not to plot"
2350 ON KEY 4 LABEL "NO PLOT" GOTO N_p
2360 ON KEY 0 LABEL "YES PLOT" GOTO Y_p
2370 GOTO 2370
2380 Y_p: ! PLOT ROUTINE
2390 OFF KEY
2400 GCLEAR

```

```

2410 GINIT
2420 GRAPHICS ON
2430 PLOTTER IS 705,"HPGL"
2440 VIEWPORT 13.5,133.0,10.5,95.0
2450 PEN 1
2460 VIEWPORT 25.1,10.30,85
2470 IF Count_out=1 THEN
2480     Max_x=.05
2490     Max_y=8
2500     Y_step=8
2510 END IF
2520 WINDOW 0,Max_x,0,Max_y
2530 AXES Max_x/10,Max_y/10,0,0
2540 CSIZE 2.0
2550 VIEWPORT 13.5,133.10.5,95
2560 LORG 4
2570 FOR I=0 TO Max_x STEP Max_x/10
2580     MOVE I,-Max_y/20
2590     LABEL USING "K";I
2600 NEXT I
2610 CSIZE 3
2620 MOVE Max_x/2,-Max_y/10
2630 IF Count_out=1 THEN LABEL USING "K";"Displacement. in"
2640 LORG 8
2650 CSIZE 2
2660 FOR I=0 TO Max_y STEP Max_y/Y_step
2670     MOVE -Max_x/35,I
2680     LABEL USING "K";I
2690 NEXT I
2700 CSIZE 3
2710 LDIR 90
2720 LORG 6
2730 MOVE -Max_x/8,Max_y/2
2740 IF Count_out=1 THEN LABEL USING "K";"Load. Kip"
2750 LDIR 0
2760 LORG 5
2770 CSIZE 1.5
2780 MOVE 0,0
2790 FOR J=1 TO Lrdg
2800     DRAW Dia(J),Lod(J)
2810 NEXT J
2820 N_p: !
2830 Count_out=Count_out+1
2840 IF Count_out<2 THEN Conv_ss
2850 I=1
2860 PRINT "Run another test? Press soft key"
2870 FOR Q=0 TO 3
2880     ON KEY Q LABEL "Run again" GOTO Cal_x
2890     ON KEY Q+5 LABEL "New set up" GOTO Set_up
2900 NEXT Q
2910 ON KEY 4 LABEL "Stop" GOTO S_10
2920 ON KEY 9 LABEL "Stop" GOTO S_10
2930 S_9: GOTO S_9
2940 S_10: STOP
2950 Test_halt: !
2960 Diam=Dia(I)*Istrain+Bstrain
2970 Strk=Stk(I)*Istroke+Bstroke
2980 Lode=Lod(I)*Iload+Bload
2990 PRINT "Test halted at:"
3000 PRINT "dia of ";Diam;" in"

```

```

3010 PRINT "stroke of ";Strk;" in"
3020 PRINT "load of ";Lode;" lbs"
3030 BEEP
3040 GOTO Cal_x
3050 Test_pause: !
3060 OFF KEY
3070 PRINT "TEST PAUSE HIT CONTINUE TO RESUME"
3080 PAUSE
3090 GOTO Data_acq
3100 Test_complete: ! STOPS DATA COLLECTION AND STORES THAT COLLECTED
3110 OFF KEY
3120 GOTO Stopper
3130 Test_dat: !SAMPLE DATA FOR VERIFYING PROGRAM
3140 Istroke=1
3150 ! Istrain=.004 ! FOR DIAM. EXTENSO. RANGE1
3160 Istrain=.010 ! FOR LONG. EXTENSO. RANGE1
3170 Iload=1
3180 ! Bstrain=.040 ! FOR DIAM. EXTENSO. RANGE1
3190 Bstrain=0 ! FOR LONG. EXTENSO.
3200 D_0=.25
3210 A_0=.049
3220 T_0=TIMEDATE
3230 Lrdg=10
3240 FOR I=1 TO 11
3250 Lod(I)=I/2
3260 Stk(I)=I/5
3270 ! Dia(I)=2*I-12 !FOR DIAM. EXTENSO.0-10V
3280 Dia(I)=I !FOR LONG. EXTENSO. 0-10V
3290 Itime(I)=TIMEDATE-T_0
3300 NEXT I
3310 GOTO Stopper
3320 R_nam: !
3330 BEEP 500,.2
3340 BEEP 1000,.2
3350 PRINT "Put in data disc!!!!!!!!!!!!!!"
3360 PRINT "Hit continue key when ready"
3370 PAUSE
3380 OFF KEY
3390 PRINT "Select old file name using soft keys"
3400 ON KEY 0 LABEL "Lod" GOTO R_nam_1
3410 ON KEY 1 LABEL "Dia" GOTO R_nam_2
3420 ON KEY 2 LABEL "Stk" GOTO R_nam_3
3430 ON KEY 4 LABEL "Itime" GOTO R_nam_5
3440 R_nam_0: GOTO R_nam_0
3450 R_nam_1:Old_file$="Lod"
3460 GOTO R_nam_8
3470 R_nam_2:Old_file$="Dia"
3480 GOTO R_nam_8
3490 R_nam_3:Old_file$="Stk"
3500 GOTO R_nam_8
3510 R_nam_5:Old_file$="Itime"
3520 GOTO R_nam_8
3530 R_nam_8: !
3540 OFF KEY
3550 INPUT "What is new file name?",New_file$
3560 RENAME Old_file$ TO New_file$
3570 PRINT USING "@.#"
3580 PRINT "Any more files to rename?"
3590 ON KEY 0 LABEL "MORE FILES" GOTO R_nam
3600 ON KEY 4 LABEL "quit" GOTO Select_

```

```

3610 R_nam_idle: GOTO R_nam_idle
3620 D_form: !
3630 OFF KEY
3640 ON ERROR GOTO Error_check
3650 PRINTER IS 1
3660 PRINT USING "@,@"
3670 PRINT "Put in data disc!!!!!!!!!!!!!!"
3680 PRINT "Then hit continue key."
3690 BEEP 100,.2
3700 BEEP 350,.2
3710 BEEP 1000,.2
3720 PAUSE
3730 PRINT "Creating Lod file"
3740 CREATE BDAT "Lod".501,8
3750 PRINT "Creating Dia file"
3760 CREATE BDAT "Dia".501,8
3770 PRINT "Creating Stk file"
3780 CREATE BDAT "Stk",501,8
3790 PRINT "Creating Itime file"
3800 CREATE BDAT "Itime",501,8
3810 GOTO Select_
3820 Error_check: !
3830 IF ERRN=54 THEN GOTO Select_
3840 PRINT "Error...ERRN is";ERRN
3850 GOTO D_form
3860 END

```



## APPENDIX D

### BASIC COMPUTER PROGRAM FOR DATA REDUCTION

```

10 !-----
20 ! PROGRAM STORED AS"JHREDUCE"
30 ! PROGRAM TO CALCULATE STRESS/STRAIN ....
40 ! FROM THE DATA COLLECTED IN "JHCOLLECT"
50 ! THEN STORE CALCULATED VALUES IN ARRAYS FOR
60 ! SUBSEQUENT PLOTTING AND CURVE FITTING
70 ! KEY VARIABLES USED:
80 !   Lod = Load
90 !   Dia = Diametral displacement
100!   Stress = True Stress
110!   Strain = True Strain
120!   Lstress = Log of True Stress
130!   Lstrain = Log of True Strain
140!   Cstress = Bridgeman corrected True Stress
150!   Clstress = Log Bridgeman Cstress
160!   Strainp = Plastic True Strain
170!   Lstrainp = Log Plastic True Strain
180!-----
190!
200! DIMENSION ARRAYS
210 DIM Lod(500),Stk(500),Dia(500),Itime(500)
220 DIM Stress(500),Strain(500)
230 DIM Lstress(500),Lstrain(500),Cstress(500)
240 DIM Lstrainp(500),Strainp(500),Clstress(500)
250 PRINT " ENSURE THE PROPER FILE NUMBERS"
260 PRINT " ARE LISTED IN THE @PATH STATEMENTS"
270 PRINT " PRIOR TO RUNNING THIS PROGRAM"
280 ! INPUT INITIAL/FINAL SPECIMEN DIAMETERS
290 ! INPUT INITIAL/FINAL NECK RADIUS OF CURVATURES
300 INPUT " ENTER INITIAL SPECIMEN DIAMETER",D_0
310 ! CALCULATE INITIAL CROSS-SECTIONAL AREA A_0
320 A_0=(PI/4)*(D_0^2)
330 PRINT "INITIAL AREA =",A_0
340 INPUT " ENTER FINAL SPECIMEN RADIUS",Rn
350 INPUT " ENTER FINAL NECK RADIUS OF CURVATURE",R
360 !COMPUTE INITIAL(CORRI) AND FINAL (CORRF)
370 !BRIDGEMAN CORRECTION FACTORS
380 ! INITIAL CORRECTION CORRI= .9723
390 !THIS FACTOR IS APPLICABLE UP TO NECKING
400 Corri=.9723
410 A=1+(2*R/Rn)
420 B=1+(Rn/(2*R))
430 Corrf=1/(A*LOG(B))
440 PRINT "FINAL CORRECTION FACTOR =",Corrf
450 INPUT "ENTER VALUE FOR YOUNG'S MODULUS",Ym
460 INPUT "ENTER MAX LOAD",Mlod
470 Count_out=1 ! COUNTING VARIABLE
480 IF Count_out>1 THEN GOTO 680
490 INPUT "CREATE FILES ? 1=YES 0= NO",Cre_ate
500 IF Cre_ate>0 THEN
510 PRINT "CREATING STRESS FILE"
520 CREATE BDAT "Stress",501,8
530 PRINT "CREATING STRAIN FILE"
540 CREATE BDAT "Strain",501,8
550 PRINT "CREATING LSTRESS FILE"
560 CREATE BDAT "Lstress",501,8
570 PRINT "CREATING LSTRAIN FILE"
580 CREATE BDAT "Lstrain",501,8
590 PRINT "CREATING CSTRESS FILE"
600 CREATE BDAT "Cstress",501,8

```

```

610 PRINT "CREATING CLSTRESS FILE"
620 CREATE BDAT "Clstress",501.8
630 PRINT "CREATING STRAINP FILE"
640 CREATE BDAT "Strainp",501.8
650 PRINT "CREATING LSTRAINP FILE"
660 CREATE BDAT "Lstrainp",501.8
670 END IF
680 ! INPUT THE PROPER Lod AND Dia FILE NUMBER
690 ! THE FILES NUMBERS MATCH THE SPECIMEN NO.
700 ! i.e. ASSIGN @PATH1 TO "Lod1"
710 BEEP 300,.5
720 PRINT " ENSURE PROPER LOD/DIA FILE DISC IN"
730 PRINT " PRESS CONTINUE TO PROCEED"
740 PAUSE
750 ASSIGN @Path1 TO "Lod"
760 ASSIGN @Path2 TO "Dia"
770 ! PATHS 3 AND 4 ARE FOR ACTUATOR STROKE AND
780 ! TEST RUN TIME AND ARE NOT USED IN PROGRAM
790 ! ENTER INTO LOD/DIA ARRAYS THE VALUES OF THE
800 ! APPROPRIATE DATA FILE FOR CALCULATION OF
810 ! STRESS,STRAIN....
820 INPUT "Specify number of data points 500 max",Rdg
830 FOR I=1 TO Rdg
840 ENTER @Path1:Lod(I)
850 ENTER @Path2:Dia(I)
860 IF Count_out=1 THEN
870 IF Lod(I)>=Mlod THEN
880 Mlod=Lod(I) ! MAX-LOAD
890 Juts=I ! DATA POINT AT MAX-LOAD
900 ! THIS IS POINT WHERE THE LINEAR CORRECTION
910 ! BEGINS TO BE APPLIED, SEE ARRAY_ASSIGN
920 PRINT "READING=",Juts
930 PRINT "MLOD=",Mlod
940 Mdia=Dia(I) ! DISP. AT MAX-LOAD
950 PRINT "MDIA=",Mdia
960 GOTO Correct_b
970 ELSE
980 Juts=Rdg
990 END IF
1000 END IF
1010 NEXT I
1020 GOTO 1230
1030 !
1040 Correct_b: !DETERMINE SLOPE AND INTERCEPT
1050 ! VALUES TO APPLY LINEAR BRIDGEMAN
1060 ! CORRECTION TO POINTS AFTER NECKING
1070 A_uts=(PI/4)*((D_0-Mdia)^2)!AREA AT MAX-LOAD
1080 Stressuts=Mlod/A_uts ! STRESS=UTS
1090 INPUT "LOAD AT FRACTURE=",Flod
1100 INPUT "FINAL DIA=",D_f
1110 A_f=(PI/4)*(D_f^2)
1120 Fstress=Flod/A_f ! STRESS AT FRACTURE
1130 Mb=(Corrf-Corri)/(Fstress-Stressuts)
1140 PRINT "MB=",Mb !SLOPE FOR LINEAR BRIDGEMAN
1150 !CORRECTION
1160 Intercept=Corrf-(Mb*Fstress) ! INTERCEPT
1170 ! VALUE FOR LINEAR BRIDGEMAN CORRECTION
1180 PRINT "INTERCEPT =",Intercept
1190 Count_out=Count_out+1
1200 ASSIGN @Path1 TO *

```

```

1210 ASSIGN @Path2 TO "
1220 GOTO 680
1230 PRINTER IS 1
1240 BEEP 200,.5
1250 PRINT "INSTALL DISC TO SAVE DATA ON"
1260 PRINT "PRESS CONTINUE TO RESUME"
1270 PAUSE
1280 ASSIGN @Path5 TO "Stress"
1290 ASSIGN @Path6 TO "Strain"
1300 ASSIGN @Path7 TO "Lstress"
1310 ASSIGN @Path8 TO "Lstrain"
1320 ASSIGN @Path9 TO "Cstress"
1330 ASSIGN @Path10 TO "Clstress"
1340 ASSIGN @Path11 TO "Strainp"
1350 ASSIGN @Path12 TO "Lstrainp"
1360 PRINT "ASSINGING VALUES TO ARRAYS"
1370 PRINTER IS 706
1380 ! COMPUTE AND ASSIGN VALUES TO ARRAYS
1390 Array_assign:
1400   FOR J=1 TO Rdg
1410     A1=(PI/4)*((D_0-D1a(J))^2)
1420     Stress(J)=Lod(J)/A1
1430     OUTPUT @Path5:Stress(J)
1440     Strain(J)=LOG(A_0/A1)
1450     OUTPUT @Path6:Strain(J)
1460     IF Stress(J)<=0 THEN
1470       Lstress(J)=0.
1480     ELSE
1490       Lstress(J)=LGT(Stress(J))
1500     END IF
1510     OUTPUT @Path7:Lstress(J)
1520     IF Strain(J)<=0 THEN
1530       Lstrain(J)=0
1540     ELSE
1550       Lstrain(J)=LGT(Strain(J))
1560     END IF
1570     OUTPUT @Path8:Lstrain(J)
1580     IF J<Juts THEN
1590       Cstress(J)=Corr1*Stress(J)
1600     ELSE
1610       Corrb=(Mb*Stress(J))+Intercept
1620       Cstress(J)=Corrb*Stress(J)
1630       PRINT "RDG=",Rdg
1640       PRINT "Dia =",D1a(J)
1650       PRINT "Corrb=",Corrb
1660     END IF
1670     OUTPUT @Path9:Cstress(J)
1680     IF Cstress(J)<=0 THEN
1690       Clstress(J)=0.
1700     ELSE
1710       Clstress(J)=LGT(Cstress(J))
1720     END IF
1730     OUTPUT @Path10:Clstress(J)
1740     Strainp(J)=Strain(J)-(Cstress(J)/Ym)
1750     OUTPUT @Path11:Strainp(J)
1760     IF Strainp(J)<=0 THEN
1770       Lstrainp(J)=0.
1780     ELSE
1790       Lstrainp(J)=LGT(Strainp(J))
1800     END IF

```

```

1810          OUTPUT @Path12:Lstrainp(J)
1820      !      PRINT "rdg's complete=","J
1830      NEXT J
1840      PRINTER IS 1
1850      BEEP 500..1
1860      PRINT "INSTALL DISC WITH LOAD/DIA DATA "
1870      PRINT "PRESS CONTINUE TO CLOSE PATHS"
1880      PAUSE
1890      ASSIGN @Path1 TO *
1900      ASSIGN @Path2 TO *
1910      BEEP 250..5
1920      PRINT "INSTALL STRESS/STRAIN...DATA DISC"
1930      PRINT "PRESS CONTINUE"
1940      PAUSE
1950      ASSIGN @Path5 TO *
1960      ASSIGN @Path6 TO *
1970      ASSIGN @Path7 TO *
1980      ASSIGN @Path8 TO *
1990      ASSIGN @Path9 TO *
2000      ASSIGN @Path10 TO *
2010      ASSIGN @Path11 TO *
2020      ASSIGN @Path12 TO *
2030      INPUT "RENAME FILES? 1=YES 0=NO",C_nt
2040      PRINT "FILE SHOULD BE RENAMED USING"
2050      PRINT "THE APPROPRIATE SECIMEN NO."
2060      IF C_nt<1 THEN
2070          GOTO 2510
2080      END IF
2090      R_nam: ! ROUTINE TO RENAME FILES
2100          BEEP 500..2
2110          BEEP 1000..2
2120          PRINT "Put in data disc!!!!!!!!!!!!!!"
2130          PRINT "Hit continue key when ready"
2140          PAUSE
2150          OFF KEY
2160          PRINT "Select old file name using soft keys"
2170          ON KEY 0 LABEL "Stress" GOTO R_nam_1
2180          ON KEY 1 LABEL "Strain" GOTO R_nam_2
2190          ON KEY 2 LABEL "Lstress" GOTO R_nam_3
2200          ON KEY 3 LABEL "Lstrain" GOTO R_nam_4
2210          ON KEY 4 LABEL "Cstress" GOTO R_nam_5
2220          ON KEY 5 LABEL "Clstress" GOTO R_nam_6
2230          ON KEY 6 LABEL "Strainp" GOTO R_nam_7
2240          ON KEY 7 LABEL "Lstrainp" GOTO R_nam_8
2250      R_nam_0: GOTO R_nam_0
2260      R_nam_1:Old_file$="Stress"
2270          GOTO R_nam_9
2280      R_nam_2:Old_file$="Strain"
2290          GOTO R_nam_9
2300      R_nam_3:Old_file$="Lstress"
2310          GOTO R_nam_9
2320      R_nam_4:Old_file$="Lstrain"
2330          GOTO R_nam_9
2340      R_nam_5:Old_file$="Cstress"
2350          GOTO R_nam_9
2360      R_nam_6:Old_file$="Clstress"
2370          GOTO R_nam_9
2380      R_nam_7:Old_file$="Strainp"
2390          GOTO R_nam_9
2400      R_nam_8:Old_file$="Lstrainp"

```

```
2410 R_nam_9:!  
2420   OFF KEY  
2430   INPUT "What is new file name?".New_file$  
2440   RENAME Old_file$ TO New_file$  
2450   PRINT USING "0.#"  
2460   PRINT "Any more files to rename?"  
2470   ON KEY 0 LABEL "MORE FILES" GOTO R_nam  
2480   ON KEY 4 LABEL "quit" GOTO 2510  
2490 R_nam_idle: GOTO R_nam_idle  
2500   BEEP 200,.5  
2510   PRINT "PROGRAM COMPLETED "  
2520   END
```



## APPENDIX E

### BASIC COMPUTER PROGRAM FOR DATA DISPLAY

```

10 ! .....
20 ! PROGRAM "JHPL0T"
30 ! THE PURPOSE OF THIS PROGRAM IS TO PLOT
40 ! THE DATA COLLECTED BY "JHCOLLECT".
50 ! THE BELOW LISTED GENERIC ARRAYS MUST
60 ! INCLUDE A SPECIMEN NO. i.e. Lod1,Dia1...
70 ! THE ARRAYS ARE:
80 !   Lod( )= THE LOAD VALUES
90 !   Dia( )= THE DIAMETRAL DISPLACEMENTS
100 !   Stk( )= MTS ACTUATOR STROKE VALUES
110 !   Itime( )= TEST RUN TIME
120 !   Stress( )= TRUE STRESS VALUES
130 !   Strain( )= TRUE STRAIN VALUES
140 !   Lstress( )= LOG TRUE STRESS VALUES
150 !   Lstrain( )= LOG TRUE STRAIN VALUES
160 !   Cstress( )= BRIDGEMAN CORRECTED TRUE
170 !               STRESS VALUES
180 !   Clstress( )= LOG BRIDGEMAN CORRECTED
190 !               TRUE STRESS VALUES
200 !   Strainp( )= PLASTIC TRUE STRAIN VALUES
210 !   Lstrainp( )= LOG PLASTIC TRUE STRAIN
220 !               VALUES
230 ! .....
240 !
250 ! DIMENSION THE ARRAYS
260 DIM Lod(500),Stk(500),Dia(500),Itime(500),Stress(500),Strain(500)
270 DIM Lstress(500),Lstrain(500),Cstress(500)
280 DIM Lstrainp(500),Strainp(500),Clstress(500)
290 BEEP 400,.5
300 PRINT " ENSURE THE PROPER FILES TO BE PLOTTED ARE LISTED  IN THE ASSIGN"
310 PRINT " @PATH STATEMENTS PRIOR TO RUNNING THIS PROGRAM"
320 PRINT
330 Count_out=0 !COUNTER
340 INPUT "Specify number of data points 500 max",Rdg
350 ! THE FOLLOWING CALCULATES FRACTURE POINT VALUES
360 INPUT "INITIAL DIAMETER",D_0
370 A_0=(PI/4)*(D_0^2)
380 INPUT "LOAD AT FRACTURE",Flod
390 INPUT "FINAL DIAMETER ",Fdia
400 Rn=Fdia/2 ! FINAL SPECIMEN RADIUS
410 INPUT "FINAL NECK RADIUS OF CURVATURE",R
420 Corrf=1/((1+(2*R/Rn))*(LOG(1+(Rn/(2*R))))))
430 PRINT "FINAL BRIDGEMAN CORR.=";Corrf
440 INPUT "ENTER YOUNG'S MODULUS",Ym
450 A_f=(PI/4)*(Fdia^2)
460 Fstress=Flod/A_f
470 Lfstress=LGT(Fstress)
480 Fstrain=LOG(A_0/A_f)
490 Lfstrain=LGT(Fstrain)
500 Cfstress=Corrf*Fstress
510 Clfstress=LGT(Cfstress)
520 Fstrainp=Fstrain-(Cfstress/Ym)
530 Lfstrainp=LGT(Fstrainp)
540 Stopper: !
550 IF Rdg>500 THEN GOTO 340
560 PRINT
570 Count_out=Count_out+1
580 PRINT "ASSIGNING PATHS"
590 IF Count_out=1 THEN
600 BEEP 100,.5

```

```

610 PRINT "INSTALL APPROPRIATE DATA DISC"
620 PRINT "PRESS CONTINUE TO RESUME"
630 PAUSE
640 IF Count_out=1 THEN
650     ASSIGN @Path1 TO "Lod"
660     ASSIGN @Path2 TO "Dia"
670 !   ASSIGN @Path3 TO "Stk"
680 !   ASSIGN @Path4 TO "Itime"
690 END IF
700 IF Count_out=2 THEN
710     ASSIGN @Path5 TO "Stress"
720 END IF
730 IF Count_out=2 OR 4 THEN
740     ASSIGN @Path6 TO "Strain"
750 END IF
760 IF Count_out=3 THEN
770     ASSIGN @Path7 TO "Lstress"
780 END IF
790 IF Count_out=3 OR 5 THEN
800     ASSIGN @Path8 TO "Lstrain"
810 END IF
820 IF Count_out=4 THEN
830     ASSIGN @Path9 TO "Cstress"
840 END IF
850 IF Count_out>=5 THEN
860     ASSIGN @Path10 TO "Clstress"
870 !   ASSIGN @Path11 TO "Strainp"
880 END IF
890 IF Count_out=6 THEN
900     ASSIGN @Path12 TO "Lstrainp"
910 END IF
920 OFF KEY
930 PRINTER IS 1
940 PRINT "ENTERING ASSIGNED PATHS"
950 FOR I=1 TO Rdg
960     IF Count_out=1 THEN
970         ENTER @Path1;Lod(I)
980         ENTER @Path2;Dia(I)
990 !     ENTER @Path3;Stk(I)
1000!     ENTER @Path4;Itime(I)
1010     END IF
1020     IF Count_out=2 THEN
1030         ENTER @Path5;Stress(I)
1040         ENTER @Path6;Strain(I)
1050     END IF
1060     IF Count_out=3 THEN
1070         ENTER @Path7;Lstress(I)
1080     END IF
1090     IF Count_out=3 OR 5 THEN
1100         ENTER @Path8;Lstrain(I)
1110     END IF
1120     IF Count_out=4 THEN
1130         ENTER @Path9;Cstress(I)
1140     END IF
1150     IF Count_out>=5 THEN
1160         ENTER @Path10;Clstress(I)
1170!     ENTER @Path11;Strainp(I)
1180     END IF
1190     IF Count_out=6 THEN
1200         ENTER @Path12;Lstrainp(I)

```

```

1210     END IF
1220     NEXT I
1230     !OUTPUT THE DATA
1240     Dat_out: !
1250     PRINT "SELECT HARD OR SOFT COPY"
1260     BEEP 900..5
1270     IF Count_out=1 THEN PRINT "LOAD/DISP"
1280     IF Count_out=2 THEN PRINT "STRESS/STRAIN"
1290     IF Count_out=3 THEN PRINT "LSTRESS/LSTRAIN"
1300     IF Count_out=4 THEN PRINT "CSTRESS/STRAIN"
1310     IF Count_out=5 THEN PRINT "CLSTRESS/LSTRAIN"
1320     IF Count_out=6 THEN PRINT "CLSTRESS/LSTRAINP"
1330     PRINT
1340     Plotz: !
1350     DEG
1360     OFF KEY
1370     PRINT "Choose whether or not to plot"
1380     ON KEY 4 LABEL "NO PLOT" GOTO N_p
1390     ON KEY 0 LABEL "YES PLOT" GOTO Y_p
1400     GOTO 1400
1410     Y_p: ! PLOT ROUTINE
1420     OFF KEY
1430     GCLEAR
1440     GINIT
1450     GRAPHICS ON
1460     PLOTTER IS 705,"HPGL"
1470     VIEWPORT 13.5,133.0,10.5,95.0
1480     PEN 1
1490     VIEWPORT 25,110,30,85
1500     IF Count_out=1 THEN !MAX COORDINATES FOR LOD VS. DIA DISPLACEMENT
1510         Max_x=.10
1520         Max_y=10
1530         Y_step=10
1540         WINDOW 0,Max_x,0,Max_y
1550         AXES Max_x/10,Max_y/Y_step,0,0
1560     END IF
1570     IF Count_out=2 THEN !MAX COORDINATES FOR STRESS/STRAIN
1580         Max_x=1.0
1590         Max_y=200
1600         Y_step=10
1610         WINDOW 0,Max_x,0,Max_y
1620         AXES Max_x/10,Max_y/Y_step,0,0
1630     END IF
1640     IF Count_out=3 THEN !MAX COORDINATES FOR LOG STRESS/STRAIN
1650         Max_x=-3.0
1660         Max_y=2.5
1670         Y_step=10
1680         WINDOW Max_x,0,.01,Max_y/.995
1690         AXES Max_x/6,Max_y/Y_step,Max_x,.01
1700     END IF
1710     IF Count_out=4 THEN !MAX COORDINATES FOR C STRESS/STRAIN
1720         Max_x=1.0
1730         Max_y=250
1740         Y_step=10
1750         WINDOW 0,Max_x,0,Max_y
1760         AXES Max_x/10,Max_y/Y_step,0,0
1770     END IF
1780     IF Count_out=5 THEN !MAX COORDINATES FOR CLSTRESS/LSTRAIN
1790         Max_x=-3.0
1800         Max_y=2.5

```

```

1810     Y_step=5
1820     WINDOW Max_x,0,.01,Max_y/.995
1830     AXES Max_x/6,Max_y/Y_step,Max_x,.01
1840     END IF
1850     IF Count_out=6 THEN !MAX COORDINATES FOR CLSTRAIN/CLSTRESS
1860         Max_x=-4.0
1870         Max_y=2.5
1880         Y_step=5
1890         WINDOW Max_x,0,.01,Max_y/.995
1900         AXES Max_x/8,Max_y/Y_step,Max_x,.01
1910         END IF
1920     CSIZE 2.0
1930     VIEWPORT 13.5,133,10.5,95
1940     LORG 4
1950     IF Count_out=1 THEN
1960         FOR I=0 TO Max_x STEP Max_x/10
1970             MOVE I,-Max_y/20
1980             LABEL USING "K";I
1990             NEXT I
2000         MOVE Max_x/2,-Max_y/8
2010         END IF
2020     IF Count_out=2 THEN
2030         FOR I=0 TO Max_x STEP Max_x/10
2040             MOVE I,-Max_y/20
2050             LABEL USING "K";I
2060             NEXT I
2070         MOVE Max_x/2,-Max_y/8
2080         END IF
2090     IF Count_out=3 THEN
2100         FOR I=0 TO Max_x STEP Max_x/6
2110             MOVE I,-Max_y/20
2120             LABEL USING "K";I
2130             NEXT I
2140         MOVE Max_x/2,-Max_y/8
2150         END IF
2160     IF Count_out=4 THEN
2170         FOR I=0 TO Max_x STEP Max_x/10
2180             MOVE I,-Max_y/20
2190             LABEL USING "K";I
2200             NEXT I
2210         MOVE Max_x/2,-Max_y/8
2220         END IF
2230     IF Count_out=5 THEN
2240         FOR I=0 TO Max_x STEP Max_x/6
2250             MOVE I,-Max_y/20
2260             LABEL USING "K";I
2270             NEXT I
2280         MOVE Max_x/2,-Max_y/8
2290         END IF
2300     IF Count_out=6 THEN
2310         FOR I=0 TO Max_x STEP Max_x/8
2320             MOVE I,-Max_y/20
2330             LABEL USING "K";I
2340             NEXT I
2350         MOVE Max_x/2,-Max_y/8
2360         END IF
2370     CSIZE 3.0
2380     IF Count_out=1 THEN LABEL USING "K";"Diametral Displacement. in."
2390     IF Count_out=2 THEN LABEL USING "K";"True Strain. in/in"
2400     IF Count_out=3 THEN LABEL USING "K";"Log True Strain"

```

```

2410 IF Count_out=4 THEN LABEL USING "K";"True Strain"
2420 IF Count_out=5 THEN LABEL USING "K";"Log True Strain"
2430 IF Count_out=6 THEN LABEL USING "K";"Log Plastic"
2440 IF Count_out=6 THEN
2450     MOVE Max_x/2,-Max_y/5
2460     LABEL USING "K";"True Strain"
2470 END IF
2480 LORG 8
2490 CSIZE 2
2500     IF Count_out=1 THEN
2510         FOR I=0 TO Max_y STEP Max_y/Y_step
2520             MOVE -Max_x/40,I
2530             LABEL USING "K";I
2540         NEXT I
2550     END IF
2560     IF Count_out=2 THEN
2570         FOR I=0 TO Max_y STEP Max_y/Y_step
2580             MOVE -Max_x/40,I
2590             LABEL USING "K";I
2600         NEXT I
2610     END IF
2620     IF Count_out=3 THEN
2630         FOR I=0 TO Max_y STEP Max_y/Y_step
2640             MOVE Max_x/.99,I
2650             LABEL USING "K";I
2660         NEXT I
2670     END IF
2680     IF Count_out=4 THEN
2690         FOR I=0 TO Max_y STEP Max_y/Y_step
2700             MOVE -Max/35,I
2710             LABEL USING "K";I
2720         NEXT I
2730     END IF
2740     IF Count_out>=5 THEN
2750         FOR I=0 TO Max_y STEP Max_y/Y_step
2760             MOVE Max_x/.99,I
2770             LABEL USING "K";I
2780         NEXT I
2790     END IF
2800 CSIZE 3.0
2810 LDIR 90
2820 LORG 6
2830 IF Count_out=1 THEN
2840     MOVE -Max_x/10,Max_y/2
2850 END IF
2851 IF Count_out=2 THEN
2852     MOVE -Max_x/8,Max_y/2
2853 END IF
2860 IF Count_out=3 THEN
2870     MOVE Max_x/.90,Max_y/2
2880 END IF
2890 IF Count_out=4 THEN
2900     MOVE -Max_x/10,Max_y/2
2910 END IF
2920 IF Count_out>=5 THEN
2930     MOVE Max_x/.91,Max_y/2
2940 END IF
2950 IF Count_out=1 THEN LABEL USING "K";"Load, Kip"
2960 IF Count_out=2 THEN LABEL USING "K";"True Stress, Ksi"
2970 IF Count_out=3 THEN LABEL USING "K";"Log True Stress(Ksi)"

```



```

2980 IF Count_out=4 THEN LABEL USING "K";"Corrected True Stress(Ks1)"
2990 IF Count_out>=5 THEN LABEL USING "K";"Log True Stress(Ks1)"
3000 IF Count_out>=5 THEN
3010     MOVE Max_x/.88,Max_y/2
3020     LABEL USING "K";"Corrected"
3030 END IF
3040 LDIR 0
3050 LORG 5
3060 CSIZE 1.5
3070 PENUP
3080 IF Count_out<3 THEN
3090     MOVE 0.0
3100 END IF
3110 IF Count_out=3 THEN
3120     PENUP
3130 END IF
3140 IF Count_out=4 THEN
3150     MOVE 0.0
3160 END IF
3170 IF Count_out=5 THEN
3180     PENUP
3190 END IF
3200 IF Count_out=6 THEN
3210     PENUP
3220 END IF
3230 ! PLOT THE VARIOUS CURVES
3240 FOR J=1 TO Rdg
3250     IF Count_out=1 THEN
3260         DRAW Dia(J),Lod(J)
3270     END IF
3280     IF Count_out=2 THEN
3290         DRAW Strain(J),Stress(J)
3300     END IF
3310 NEXT J
3320 IF Count_out=3 THEN
3330     FOR J=1 TO Rdg
3340         MOVE Lstrain(J),Lstress(J)
3350         DRAW Lstrain(J),Lstress(J)
3360     NEXT J
3370 ! PLOT FRACTURE POINT
3380     MOVE Lfstrain,Lfstress
3390     LABEL USING "K";"*"
3400     END IF
3410     IF Count_out=4 THEN
3420         FOR J=1 TO Rdg
3430             DRAW Strain(J),Cstress(J)
3440         NEXT J
3450 !PLOT FRACTURE POINT
3460         MOVE Fstrain,Cfstress
3470         LABEL USING "K";"*"
3480         END IF
3490         IF Count_out=5 THEN
3500             FOR J=5 TO Rdg
3510                 MOVE Lstrain(J),Clstress(J)
3520                 DRAW Lstrain(J),Clstress(J)
3530             NEXT J
3540 ! PLOT FRACTURE POINT
3550             MOVE Lfstrain,Clfstress
3560             LABEL USING "K";"*"
3570             END IF

```

```

3580 IF Count_out=6 THEN
3590 ! THIS ROUTINE PLOTS LOG CORRECTED TRUE STRESS VS. LOG PLASTIC TRUE
3600 FOR J=27 TO Rdg ! J= THE FIRST PLASTIC STRAIN >.001 LOG TRUE STR
3610 ! THIS VALUE MUST BE ENTERED FOR EACH SPECIMEN
3620 MOVE Lstrainp(J),Clstress(J)
3630 DRAW Lstrainp(J),Clstress(J)
3640 NEXT J
3650 ! PLOT FRACTURE POINT
3660 MOVE Lfstrainp.Clfstress
3670 LABEL USING "K";""
3680 END IF
3690 PEN Up
3700 ! GRAPH TITLE
3710 VIEWPORT 13.5,133.0,10.5,95.0
3720 LDIR 0
3730 CSIZE 4
3740 MOVE Max_x/2,Max_y/.90
3750 INPUT "ENTER SPECIMEN NO.",No
3760 LABEL USING "K";"HSLA-100 HOURGLASS"
3770 MOVE Max_x/2,Max_y/.95
3780 LABEL USING "K";"SPECIMEN NO.",No
3790 PENUP
3800 IF Count_out=1 THEN PRINT "LOAD/DISP"
3810 IF Count_out=2 THEN PRINT "STRESS/STRAIN"
3820 IF Count_out=3 THEN PRINT "LSTRESS/LSTRAIN"
3830 IF Count_out=4 THEN PRINT "CSTRESS/STRAIN"
3840 IF Count_out=5 THEN PRINT "CTSTRESS/LSTRAIN"
3850 IF Count_out=6 THEN PRINT "CLSTRESS/LSTRAINP"
3860 ON KEY 0 LABEL "HARD COPY" GOTO Har
3870 ON KEY 4 LABEL "SOFT COPY" GOTO Sof
3880 Stop_idle: GOTO Stop_idle
3890 Har: PRINTER IS 706
3900 Sof:
3910 OFF KEY
3920 IF Count_out=1 THEN
3930 PRINT " I LOAD DISPL STROKE TIME"
3940 PRINT " (KIP) (IN) (IN) (SEC)"
3950 FOR I=1 TO Rdg
3960 PRINT USING Fmt1:I,Lod(I),Dia(I),Stk(I),Itime(I)
3970 NEXT I
3980 END IF
3990 IF Count_out=2 THEN
4000 PRINT " I STRESS STRAIN "
4010 PRINT " (Ksi) (In/In) "
4020 FOR I=1 TO Rdg
4030 PRINT USING Fmt2:I.Stress(I),Strain(I)
4040 NEXT I
4050 END IF
4060 IF Count_out=3 THEN
4070 PRINT " I LSTRESS LSTRAIN "
4080 FOR I=5 TO Rdg
4090 PRINT USING Fmt2:I.Lstress(I),Lstrain(I)
4100 NEXT I
4110 END IF
4120 IF Count_out=4 THEN
4130 PRINT " I CSTRESS STRAIN"
4140 FOR I=1 TO Rdg
4150 PRINT USING Fmt2:I.Cstress(I),Strain(I)
4160 NEXT I
4170 END IF

```

```

4180 IF Count_out=5 THEN
4190 PRINT " I          CLSTRESS  LSTRAIN"
4200 FOR I=5 TO Rdg
4210 PRINT USING Fmt2;I,Clstress(I),Lstrain(I)
4220 NEXT I
4230 END IF
4240 IF Count_out=6 THEN
4250 PRINT " I          CLSTRESS  LSTRAINP "
4260 FOR I=23 TO Rdg
4270 PRINT USING Fmt2;I,Clstress(I),Lstrainp(I)
4280 NEXT I
4290 END IF
4300 Fmt1: IMAGE DDD,5X,2(1X,SD,DDDE)
4310 Fmt2: IMAGE DDD,5X,2(1X,SD,DDDE)
4320 N_p: !
4330 OFF KEY
4340 IF Count_out<6 THEN GOTO Stopper
4350 ASSIGN @Path1 TO *
4360 ASSIGN @Path2 TO *
4370 ASSIGN @Path3 TO *
4380 ASSIGN @Path4 TO *
4390 ASSIGN @Path5 TO *
4400 ASSIGN @Path6 TO *
4410 ASSIGN @Path7 TO *
4420 ASSIGN @Path8 TO *
4430 ASSIGN @Path9 TO *
4440 ASSIGN @Path10 TO *
4450 ASSIGN @Path11 TO *
4460 ASSIGN @Path12 TO *
4470 OFF KEY
4480 ON KEY 4 LABEL "Stop" GOTO S_10
4490 ON KEY 0 LABEL "RERUN" GOTO 330
4500 Pause_idle: GOTO Pause_idle
4510 S_10:STOP
4520 PRINT "PROGRAM COMPLETED"
4530 END

```

## APPENDIX F

### BASIC COMPUTER PROGRAM FOR CONSTITUTIVE EQUATION TESTING

```

1      ! .....
3      ! PROGRAM STORED AS "POWERFIT"
10     ! THE PURPOSE OF THIS PROGRAM IS TO PLOT
11     ! LOG BRIDGEMAN CORRECTED TRUE STRESS VS
12     ! THE PURPOSE OF THE PROGRAM IS:
13     ! 1. TO APPLY A POWER FUNCTION FIT BY THE
14     !    METHOD OF LEAST SQUARES, TO THE LOG
15     !    BRIDGEMAN CORRECTED TRUE STRESS/LOG
16     !    PLASTIC TRUE STRAIN VALUES FOR EACH
17     !    HSLA-100 STEEL SPECIMEN TESTED.
18     ! 2. COMPUTATION OF THE STRAIN HARDENING
19     !    EXPONENT, M, AND THE STRENGTH
20     !    COEFFICIENT, K1. PLOT A STRAIGHT LINE
21     !    BETWEEN LOG PLASTIC STRAIN = .001 AND
22     !    1.0 USING SLOPE, M, AND INTERCEPT LOG
23     !    K1. THIS LINE OVERLAYS THE PLOT OF
24     !    BRIDGEMAN CORRECTED TRUE STRESS VS.
25     !    LOG PLASTIC TRUE STRAIN.
26     ! 3. COMPUTE THE CORRELATION COEFFICIENT, R,
27     !    AS A MEASURE OF THE FIT BETWEEN THE
28     !    TWO CURVES.
29     ! 4. ARRAY VALUES CAN BE PRINTED OUT
31     ! .....
32     !
33     ! POWER EQ. FORM  $\text{LOG}(\text{STRESS}) = \text{LOG}(K1) + M \text{LOG}(\text{STRAIN})$ 
34     ! STRESS IS THE BRIDGEMAN CORRECTED TRUE STRESS
40     ! STRAIN IS THE TRUE PLASTIC STRAIN
50     ! THE EXPRESSION SHOULD YIELD A LINEAR RELATION
60     ! M IS THE SLOPE OF THE LINE AND IS CALLED THE STRAIN HARDENING EXPONENT
70     ! INTERCEPT CALCULATIONS YIELD THE VALUE FOR K1
71     ! DIMENSION ARRAYS
80     DIM Clstress(500), Lstrainp(500)
90     PRINT "ENSURE APPROPRIATE FILE NO. IS FOLLOWING THE Clstress/Lstrainp arrays"
100    PRINT
110    PRINT " APPROPRIATE DATA DISC MUST BE INSTALLED TO RUN PROGRAM"
120    ! CALCULATE BRIDGEMAN CORRECTION AT FRACTURE CORRF
130    INPUT "FINAL SPECIMEN RADIUS, Rn", Rn
140    INPUT "FINAL NECKED RADIUS OF CURVATURE, R", R
150    Corrf = 1 / ((1 + 2 * R / Rn) * (LOG(1 + Rn / (2 * R))))
160    PRINT "FINAL CORRECTION FACTOR = "; Corrf
161    ! THE BRIDGEMAN CORRECTION TO POINTS 1-RDG
162    ! HAS BEEN DETERMINED AND APPLIED IN CSTRESS
163    ! WHEN THE CSTRESS ARRAY WAS GENERATED.
164    ! THEN THE LGT OF THOSE ARRAY POINTS WAS TAKEN
165    ! TO YIELD THE CLSTRESS ARRAY.
166    ! THESE MANIPULATIONS WERE DONE BY "JHREDUCE"
167    ! THUS THE CLSTRESS ARRAY IN THIS PROGRAM
168    ! HAS THE CORRECTED VALUES IN IT
169    !
170    ! DETERMINE THE FRACTURE POINT
171    ! CORRECTED LSTRESS/LSTRAINP VALUES
173    INPUT "YOUNG'S MODULUS, YM IN KSI", Ym
174    INPUT "INITIAL SPECIMEN DIAMETER", D_0
175    A_0 = (PI/4) * (D_0^2)
176    D_f = 2 * Rn
177    A_f = (PI/4) * (D_f^2)
178    INPUT "LOAD AT FRACTURE", Flod
179    Fstress = Flod / A_f
180    Fstrain = LOG(A_0 / A_f)
181    Cfstress = Corrf * Fstress

```

```

184      Lc+stress=LGT(Cfstress)
185      Fstrainp=Fstrain-(Cfstress/Ym)
188      Lfstrainp=LGT(Fstrainp)
189      PRINT "LCFSTRESS=",Lcfstress
190      PRINT "LFSTRAINP =",Lfstrainp
192      ASSIGN @Path1 TO "Clstress5"
193      ASSIGN @Path2 TO "Lstrainp5"
200      INPUT "SPECIFY NUMBER OF ARRAY POINTS 500 MAX",Rdg
210      FOR I=1 TO Rdg
220          ENTER @Path1:Clstress(I)
230          ENTER @Path2:Lstrainp(I)
240      NEXT I
250      !OUTPUT DATA
260      PRINT "SELECT HARD COPY OR SCREEN OUTPUT OF"
270      PRINT "THE Lstrainp and Clstress arrays"
290      OFF KEY
290      ON KEY 0 LABEL "HARD COPY" GOTO Har!
300      ON KEY 4 LABEL "SOFT COPY" GOTO Sof!
310      Stop_idle:      GOTO Stop_idle
320      Har!:      PRINTER IS 705
330      Sof!:      !
340      OFF KEY
350      PRINT "I      CLSTRESS      LSTRAINP"
360      FOR I=1 TO Rdg
370          PRINT USING Fmt1:I:Clstress(I),Lstrainp(I)
380      NEXT I
390      Fmt1: IMAGE DDD.5X.2(1X.SD.DDDE)
400      ! FIT A STRAIGHT LINE TO THE ORDERED PAIRS
410      ! Lstrainp(I),Clstress(I)
420      ! SOLVING THE SIMULTANEOUS EQUATIONS AS
430      ! LISTED IN THE CRC HANDBOOK
440      ! A AND B ARE THE FRACTURE POINT Lstrainp and Clstress values respectively
450      A=Lfstrainp ! FRACTURE POINT LSTRAINP
460      B=Lcfstress !FRACTURE POINT LCFSTRESS
470      C=A*B
480      D=A^2
490      E=C
500      F=B^2
510      G=0
520      NO=1 ! DATA PAIR COUNTER INCLUDES FRACTURE POINT
530      ! THE INITIAL VALUE FOR I IS USER INPUTTED
550      INPUT " FIRST DATA POINT,RDG =",First
551      ! THIS SHOULD BE THE FIRST POINT WITH LSTRAINP
552      ! GREATER THAN -3.0
560      FOR I=First TO Rdg
570          A0=A+Lstrainp(I)
580          A=A0 !NOW A IS SUMMING VARIABLE
590          B0=B+Clstress(I)
600          B=B0 !NOW B IS SUMMING VARIABLE
610          C0=C+(Clstress(I)*Lstrainp(I))
620          C=C0 !NOW C IS SUMMING VARIABLE
630          D0=D+(Lstrainp(I)^2)
640          D=D0 !NOW D IS SUMMING VARIABLE
650          F0=F+(Clstress(I)^2)
660          F=F0 !NOW F IS SUMMING VARIABLE
670          NO=NO+1 !COUNTER FOR DATA PAIRS
680      NEXT I
690      N=NO
700      E=A^2
710      G=B^2

```

```

700 OFF KEY
710 PRINT "SELECT HARD COPY OR SCREEN OUTPUT OF"
720 PRINT "THE DATA OUTPUT"
730 ON KEY 0 LABEL "HARD COPY" GOTO Har2
740 ON KEY 4 LABEL "SCREEN OUTPUT" GOTO Sof2
750 GOTO 750
760 Har2:PRINTER IS 706
770 Sof2:!
780 INPUT "SPECIMEN NO.="No
800 INPUT "TEST TEMPERATURE=",Tt
810 PRINT
820 PRINT "          HSLA-100 HOURGLASS"
830 PRINT "          SPECIMEN NO.",No
831 PRINT
840 PRINT "          TEST TEMPERATURE =",Tt;"DEG. C"
850 PRINT
860 PRINT "          YOUNG'S MODULUS =",Ym;" Ksi"
870 PRINT
880 PRINT "          FIRST DATA POINT =",First
890 PRINT
920 !COMPUTE STRAIN HARDENING EXPONENT,K1 AND
930 PRINT
940 !SLOPE OF LINE M
950 PRINT "          NUMBER OF DATA PAIRS=";N
960  $M = ((N * C) - (A * B)) / ((N * D) - E)$ 
970  $K1 = (B / N) - (M * A / N)$ 
980 PRINT
990 PRINT "          SLOPE = ";M
1000 PRINT
1010 PRINT "          INTERCEPT = ";K1
1020 PRINT
1030 ! COMPUTE CORRELATION R
1040  $Corcoef = ((N * C) - (A * B)) / \text{SQR}(((N * D) - E) * ((N * F) - G))$ 
1050 PRINT "          CORRELATION COEFFICIENT,R =",Corcoef
1060 PRINT
1070 PRINTER IS 1
1080 Count_out=1
1090 Plotz: !
1100 DEG
1110 OFF KEY
1120 PRINT "Choose whether or not to plot"
1130 ON KEY 4 LABEL "NO PLOT" GOTO N_p
1140 ON KEY 0 LABEL "YES PLOT" GOTO Y_p
1150 GOTO 1150
1160 Y_p: ! PLOT ROUTINE
1170 OFF KEY
1180 GCLEAR
1190 GINIT
1200 GRAPHICS ON
1210 PLOTTER IS 705,"HPGL"
1220 VIEWPORT 13.5,133.0,10.5,95.0
1230 PEN 1
1240 VIEWPORT 25,110,30,85
1250 ! Max_x=-4.0
1260 Max_x=-3.0
1270 Max_y=2.5
1280 Y_step=5
1290 WINDOW Max_x,0,.01,Max_y/.995
1300 AXES Max_x/76,Max_y/Y_step,Max_x,.01
1310 CSIZE 2.0

```



```

1320 VIEWPORT 13.5,133,10.5,95
1330 LORG 4
1340   FOR I=0 TO Max_x STEP Max_x/6
1350     MOVE I,-Max_y/20
1360     LABEL USING "K";I
1370     NEXT I
1380   MOVE Max_x/2,-Max_y/8
1390   CSIZE 3.0
1400   LABEL USING "K";"Log Plastic"
1410   MOVE Max_x/2,-Max_y/5
1420   LABEL USING "K";"True Strain"
1430 LORG 8
1440 CSIZE 2
1450   FOR I=0 TO Max_y STEP Max_y/Y_step
1460     MOVE Max_x/.99,I
1470     LABEL USING "K";I
1480     NEXT I
1490 CSIZE 3.0
1500 LDIR 90
1510 LORG 6
1520   MOVE Max_x/.91,Max_y/2
1530   LABEL USING "K";"Log True Stress(Ks1)"
1540   MOVE Max_x/.88,Max_y/2
1550   LABEL USING "K";"Corrected"
1560 LDIR 0
1570 LORG 5
1580 CSIZE .5
1590 ! THIS ROUTINE PLOTS LOG CORRECTED TRUE STRESS VS. LOG PLASTIC STRAIN
1600   FOR J=First TO Rdg
1610     MOVE Lstrainp(J),Clstress(J)
1620     DRAW Lstrainp(J),Clstress(J)
1630     LABEL USING "K";"*"
1640   NEXT J
1650 PENUP
1660 ! PLOT FRACTURE POINT
1670 CSIZE .5
1680   MOVE Lfstrainp,Lcfstress
1690   LABEL USING "K";"*"
1700 ! PENUP
1710 ! THIS SECTION PLOTS THE CURVE FIT LINE
1720 ! FIRST POINT CORRESPONDS TO A STRAIN OF .001
1730 ! THE SECOND POINT CORRESPONDS TO A STRAIN OF 1.0
1740   X1=-3.0
1750   Y1=(M*X1)+K1
1760   MOVE X1,Y1
1770   X2=0
1780   Y2=(M*X2)+K1
1790   BEEP 500,.2
1800   PRINT "CHANGE COLOR OF PEN ? 30 SEC DELAY"
1810 ! PRINT "PRESS PEN DOWN"
1820   WAIT 30
1830   DRAW X1,Y1
1840   DRAW X2,Y2
1850 ! GRAPH TITLE
1860 VIEWPORT 13.5,133,0,10.5,95,0
1870 LDIR 0
1880 CSIZE 4
1890 MOVE Max_x/2,Max_y/.90
1900 INPUT "ENTER SPECIMEN NO. ",No
1910 LABEL USING "K";"HSLA-100 HOURGLASS"

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1990     MOVE Max_x/2,Max_y/.95
2000     LABEL USING "K";"SPECIMEN NO.",No
2010     PENUP
2020     N_p: !
2030     OFF KEY
2040     Count_out=Count_out+1
2050     IF Count_out>1 THEN
2060     ASSIGN @Path1 TO *
2070     ASSIGN @Path2 TO *
2080     ELSE
2090     GOTO Plotz
2100     END IF
2110     OFF KEY
2120     PRINTER IS 1
2130     ON KEY 4 LABEL "Stop" GOTO S_10
2140     ON KEY 0 LABEL "RERUN" GOTO 192
2150     Pause_idle: GOTO Pause_idle
2160     S_10:STOP
2161     PRINT "PROGRAM COMPLETE"
2170     END

```

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